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NEUTRON TIME-OF-FLIGHT STUDIES

OF

B^{10} , C^{11} , AND NE^{20}

by

Peter Julian Riley

A THESIS

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ABSTRACT

The $\text{Be}^9(\text{d},\text{n})\text{B}^{10}$ reaction has been studied using time-of-flight techniques. Neutron groups leading to the 5.11 and 5.16 Mev states in B^{10} have been resolved. Angular distribution measurements have been made on neutrons leading to the 5.16, 5.11, and 4.77 Mev states. Analysis of these distributions in terms of plane-wave Butler stripping theory is given. Partial width measurements indicate that the 5.11 and 4.77 Mev levels of B^{10} decay almost entirely by alpha emission, and that the 5.16 Mev level decays almost entirely by gamma emission. The results are consistent with the respective assignments of $J^\pi = 2^+, T = 1$, $J^\pi = 2^-, T = 0$, and $T = 0$ for the 5.16, 5.11, and 4.77 Mev states. No evidence was seen for the broad 5.18 Mev level in B^{10} .

The decay of the 6.48 Mev level in C^{11} has been studied by means of the $\text{B}^{10}(\text{d},\text{n}\gamma)\text{C}^{11}$ reaction. Gamma-rays from the decay of this state were observed using a collimated 4 inch by 4 inch NaI crystal. The NaI crystal was gated by neutrons leading to the 6.48 Mev state. The results give a value of the branching ratio for direct ground-state transitions relative to cascades through the 4.26 Mev level of $8 \pm 1 : 1$. This measurement is in good agreement with the intermediate-coupling-model prediction.

Preliminary $\text{F}^{19}(\text{d},\text{n})\text{Ne}^{20}$ neutron time-of-flight spectra have been recorded. Using a pulsed beam, neutron groups leading to states in Ne^{20} at 1.63, 4.97, 5.64, 6.75, 9.34, and 9.97 Mev have been tentatively identified. Neutron-gamma coincidence spectra indicated states in Ne^{20} at 9.34, 9.97, and 10.9 Mev.

Abstract continued

Unsuccessful attempts have been made to "bunch" at low energy an ion beam obtained from an rf-excited ion source. A method of ion-pulsing by means of a grid arrangement located immediately after the ion-source extractor canal was investigated. The pulse duration obtained was not as short as that obtainable from a pre-acceleration deflector plate system.

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CHAPTER I. INTRODUCTION

The main part of this thesis describes time-of-flight measurements on neutrons produced in the $\text{Be}^9(\text{d},\text{n})\text{B}^{10}$, $\text{B}^{10}(\text{d},\text{n})\text{C}^{11}$, and $\text{F}^{19}(\text{d},\text{n})\text{Ne}^{20}$ reactions. The measurements were made by means of a fast neutron time-of-flight spectrometer designed by Neilson et al, and used in conjunction with the University of Alberta 2 Mev Van de Graaff accelerator (Ne 59). The final chapter of this thesis describes attempts to develop a new ion pulsing system for the Van de Graaff, and so to improve the operation of the neutron spectrometer.

The (d,n) and $(\text{d},\text{n}\gamma)$ reactions investigated in this thesis can usually be reasonably well described by a deuteron stripping mechanism. In a (d,n) stripping reaction, the proton of the loosely bound deuteron is captured by the target nucleus, the neutron passing so far away that its interaction with the nucleus may be neglected. In a $(\text{d},\text{n}\gamma)$ reaction, excited states of the residual nucleus then decay by gamma emission. Stripping reactions are characterized by strong forward maxima in the angular distributions of the outgoing particles.

A detailed treatment of stripping reactions is beyond the scope of this introduction; however, much useful information can be obtained by simple arguments. The simple theory assumes that (a) all effects of Coulomb repulsion and nuclear scattering of the deuteron and outgoing particle may be neglected, (b) there is no compound nucleus formation, and (c) the captured particle reacts with the target nucleus only on the surface of a sphere of radius R (Bu 57a). That is, for (d,n) stripping,

the proton hits the target and is absorbed, while the neutron continues on with whatever momentum it had at the instant of collision to be counted as a reaction product.

Qualitatively, the angular distribution should be strongly peaked in the forward direction. The shape of the angular distribution of emitted neutrons is strongly dependent on ℓ_p , the angular momentum with which the proton is captured. Conservation of angular momentum and parity restricts the possible values of ℓ_p , since the change in angular momentum between the initial and final nuclei must be provided by the total angular momentum with which the proton enters the target. If J_i and J_e are respectively the spins of the target nucleus and the particular state in which the residual nucleus is left, then

$$|J_i - J_e| - \frac{1}{2} \leq \ell_p \leq J_i + J_e + \frac{1}{2}$$

For conservation of parity, ℓ_p is even if the states J_i and J_e have similar parities, and odd if the states have opposite parities.

A classical argument can be used to indicate the effect of the allowed values of ℓ_p on the angular distribution (Be 60). $\ell_p = k b$, where k is the momentum of the proton approaching the target, and b is the impact parameter, which cannot be greater than the nuclear radius if the proton is to be absorbed. That is,

$$k = \frac{\ell_p}{b} \geq \frac{\ell_p}{R}$$

k is provided partly by the external motion of the deuteron and partly by the internal motion of the nucleon while bound in the deuteron. The latter contribution is a strongly decreasing function of k , so that if $\ell_p = 0$ is allowed, a peak occurs in the angular distribution at $k = 0$, with smaller peaks for higher allowed ℓ_p values. If $\ell_p = 0$ is not allowed, a peak occurs at $k = 1/R$ times

the smallest ℓ_p value allowed, again with further peaks for higher ℓ_p . If θ is the angle between the incident beam and the outgoing neutron, small θ corresponds to small k , since if the outgoing neutron stays close to the deuteron beam direction, k gets little contribution from the internal motion of the deuteron. Similarly, a large θ corresponds to large k , since the proton receives a large push to conserve momentum in the deuteron's center of mass.

Quantum-mechanically, in the treatment of Bhatia et al (Bh 52), the differential cross-section in the center of mass system can be written

$$\sigma(\theta) = \pi(K_n) \sum_{\ell_p} P(\ell_p) L_{\ell_p}(k_p)$$

where $\pi(K_n)$ is the probability that the neutron has the momentum contribution $\hbar K_n$ from the internal motion of the deuteron, $L_{\ell_p}(k_p)$ is the centrifugal barrier factor of a proton with angular momentum $\hbar k_p$, and $P(\ell_p)$ is the probability that a proton reaching the "surface" of the target nucleus with angular momentum ℓ_p will be captured. The zero-range approximation to the deuteron wave function gives

$$\pi(K_n) = \frac{\alpha}{\pi^2(\alpha^2 + K_n^2)^2}, \quad \alpha = 2.3 \times 10^{-12} \text{ cm}^{-1}.$$

The barrier factor $L_{\ell_p}(k_p)$ is given by

$$L_{\ell_p}(k_p) = 4\pi(2\ell_p + 1) j_{\ell_p}^2(k_p R)$$

where j_{ℓ_p} is a spherical Bessel function and R is the radius at which the proton is supposed to be captured. R is usually considered to be a somewhat adjustable parameter. $P(\ell_p)$ contains a factor dependent on the properties of the initial and final nuclear levels, and is independent of k and θ . The angular dependence of the

cross section is determined mainly by the centrifugal barrier factor $L_{\ell_p}(k_p)$. Assuming that one value of ℓ_p dominates, which is nearly always the case, the angular dependence can be written as

$$\sigma(\theta) \simeq \Pi(K_n) j_{\ell_p}^2(k_p R)$$

For $\ell_p = 0$, the maximum of $\sigma(\theta)$ occurs at $\theta = 0$; for $\ell_p = 1$, the maximum usually occurs near $\theta = 20^\circ$, and so on.

There have been many refinements to the simple theory; Coulomb repulsion, nuclear scattering of the deuteron and outgoing particle, and compound nucleus formation all affect the form of the cross section. Present-day treatment of stripping often considers distorted-wave approximations for the ingoing and outgoing particles instead of the plane-wave approximations of the simple theory, and uses optical model nuclear wave functions. However, the simple theory of deuteron stripping has had remarkable success, and is easy to apply to experimentally observed angular distributions.

In a $(d, n\gamma)$ reaction, radiation from an excited state of a residual nucleus may show a non-isotropic directional correlation with the emitted particle corresponding to that state. If the Butler stripping assumptions apply, the angular correlation in the plane containing the deuteron beam and the emitted particle is symmetric about the recoil direction of the residual nucleus (Ne 60). If the Butler assumptions do not apply, triple correlation functions must be used.

The simple stripping theory described above was used in the analysis of angular distribution data on neutrons leading to states of B^{10} (see Chapter III). The neutron time-of-flight spectrometer is briefly described in Chapter II. The spectrometer can also be employed to select a particular excited state, whose decay can then be studied. Chapter IV

describes the measurement of the decay scheme of the 6.48 Mev level of C^{11} using the neutron spectrometer to gate a NaI detector. The results were, however, dependent on any angular correlation between neutrons leading to the 6.48 Mev state and gamma-rays emitted during the decay of this level.

The final chapter of this thesis describes the pulsing of an ion beam, and so is not directly related to the work described in the preceeding chapters. However, new techniques of ion pulsing are contributing greatly to the performance of fast neutron time-of-flight spectrometers. The best present-day results are, in general, possible with the best ion-pulsing system, and consequently ion pulsing systems have become increasingly complex and expensive.

Ion pulsing refers to the production of discrete bursts of ions of short time duration. The usual reason for pulsing a beam of ions from an accelerator is to produce corresponding pulses of neutrons from some suitable target. Since the time of origin of the neutrons is then localized to the pulse duration, the neutron velocities can then be measured by means of a fast neutron time-of-flight spectrometer. The shorter the burst duration, the more precise the energy measurements can be. Similarly, a high burst intensity enables long flight paths to be used, making possible good energy resolution. The two requirements of short time duration and a high burst intensity are almost directly opposing; consequently, the engineering problems involved are difficult. It is no longer sufficient just to "chop" a dc beam from a Van de Graaff accelerator into pulses of short time duration, so wasting nearly all of the original beam. Recently, methods have been developed of

"bunching" a beam of ions (Co 61). It was hoped to be able to develop a more simple method of ion bunching for use in this laboratory than the complex systems now available.

CHAPTER II. THE FAST NEUTRON SPECTROMETER

I. Description of Spectrometer

The experimental work described in Chapters III, IV, and V of this thesis is based upon neutron time-of-flight measurements using a spectrometer designed by Neilson et al (Ne 59, Ne 60, Ne 62) and used in conjunction with the University of Alberta 2 Mev Van de Graaff generator. The operation of the spectrometer is fully described in the above references; therefore, only a brief description of the spectrometer is given here.

The purpose of the spectrometer is to detect and to measure the flight time of neutrons originating from a target, and so to enable the determination of neutron energies and momenta. Figure 2-1 shows how these functions are performed. For each detected neutron there corresponds two pulses; a "start", or "zero-time" pulse, related to the time of emission of the neutron, and a "stop", or "timing" pulse, related to the time of arrival of the neutron at the detector. The relative timing of these two pulses is measured by a time-to-pulse-height converter, or "time-sorter". The amplitude of the output pulse of this circuit is proportional to the overlap of the start and stop pulses. Therefore, the amplitude of the output pulse can be written as $V = V_{\max}(1 - t/T)$, where T is the length of the start and stop pulses, and represents the maximum time span which can be covered in a single run. In the experiments to be described, $T = 150$ nsec. Since for non-relativistic neutrons, the flight time, $t = 72.3/\sqrt{E}$ nsecs per meter, where E is the energy in Mev, the neutron energy is easily obtained.

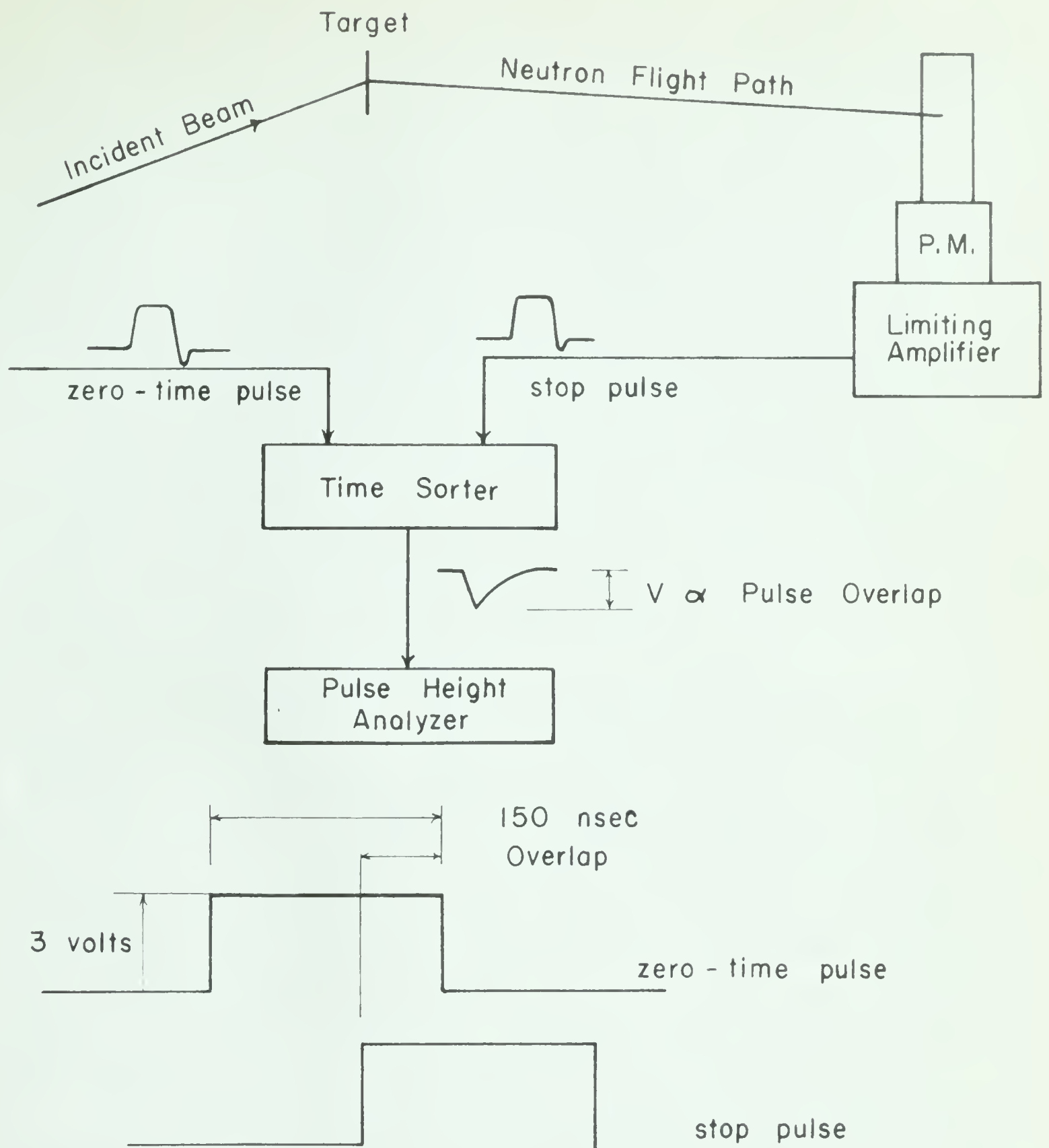


Figure 2-1 Principle of operation of the fast neutron spectrometer.

The stop, or timing pulse, is derived from a 9" x 3" x 1-1/2" liquid scintillator*, which feeds an R.C.A. 7046 photomultiplier and limiting amplifier. The start, or zero-time pulse, can be derived by two alternative methods. In the coincidence method, the zero-time determination is based on the detection of a gamma-ray which occurs simultaneously with the emission of a neutron. The pulsed beam method restricts the time of emission of neutrons from the target to the duration of short bursts of beam on the target; the start pulses are then determined by the time of arrival of the pulses of beam at the target. The coincidence method can, of course, only be used to study neutron groups leading to gamma emitting states; the pulsed beam technique gives a zero-time independent of the reaction.

A block diagram of the complete spectrometer with the start pulse derived by the coincidence method is given in Figure 2-2. The gamma detector, a 3" diameter x 4" long NE 102** plastic phosphor, is normally placed as close as possible to the target. A serious limitation of this method involves the necessarily high counting rate in the gamma detector. For high resolution work, the counting rate in the detector should not exceed 5×10^4 counts per second. Thus, in a given experiment, the d.c. beam current should be adjusted so that this counting rate is not exceeded.

The gamma and neutron side channels allow some energy selection if the neutron and gamma-ray spectra are complex, and also serve to eliminate pulses too small to operate the time-sorter properly. The negative-time-eliminator rejects any chance coincidences for which the pulse from the neutron counter, or stop pulse, precedes the start

*NE 213 Liquid Scintillator, Nuclear Enterprises, Ltd., Winnipeg, Manitoba.

**Nuclear Enterprises, Ltd., Winnipeg, Manitoba.

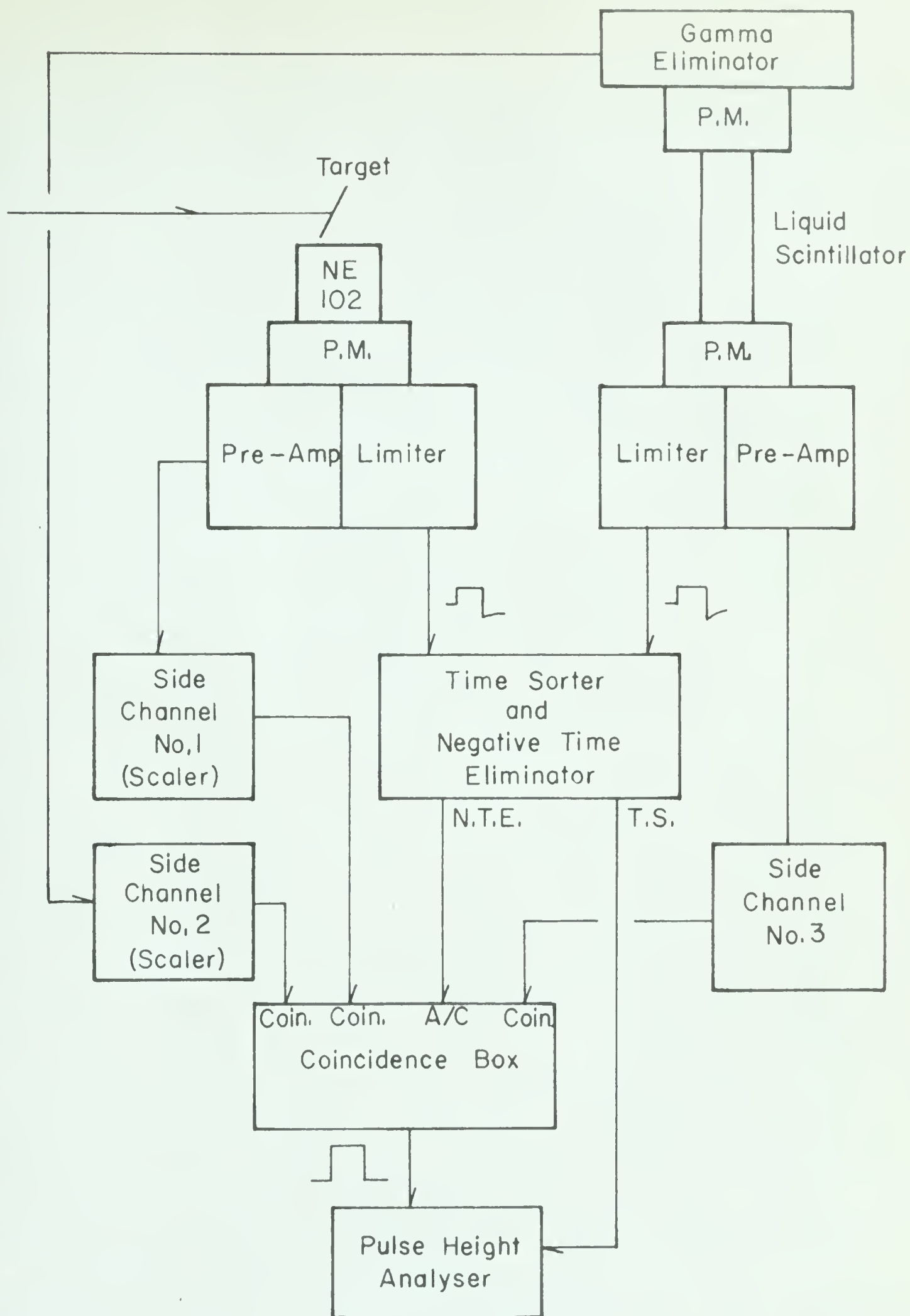


Figure 2-2 Block diagram of the spectrometer.

pulse. The gamma-eliminator circuit, by analysis of the decay times of the liquid scintillator pulse, distinguishes between pulses caused by gamma-rays and recoil protons. By eliminating random counts due to gamma-rays, most of the background in the neutron counter is removed.

Figure 2-3 is a block diagram indicating how the beam is pulsed and the zero-time pulse obtained. Beam pulsing will be discussed in more detail in Chapter VI; briefly, a deflecting voltage, here of approximately 10 kev peak to peak and 1.67 MC frequency, is applied to the first set of polished brass plates (20" x 2"; 2" apart). The major part of the unwanted deflected beam is then caught in re-entrant cups of high Z, called "scraper" slits, placed some 8 mm apart 10 cm beyond the plates. Only ions which traverse the field near zero phase can pass through the slits. Therefore, two current bursts per rf cycle are obtained, the "upsweep" and the "down-sweep", with a phase separation of 180° . Since the two sweeps are physically separated at the target, and may even contain differing amounts of current, it is usually desirable to eliminate one of them. This function is performed by the second set of deflector plates, which is therefore called the alternate pulse eliminator, or APE. The phase between the two sets of plates is adjusted by means of the phase shifter so that the two bursts derived in the first set of plates pass through the second set of plates near maximum phase. The bursts therefore receive opposite impulses during their passage through the APE, and become sufficiently separated that one sweep can be eliminated entirely by adjustment of beam defining slits.

The start pulse is derived from the sinusoidal deflecting voltage by means of a pick-up loop. The induced signal is taken through a squaring circuit, the output of which is shaped to provide one zero-time pulse per rf cycle, and fed into the time-sorter. Thus, use is made of

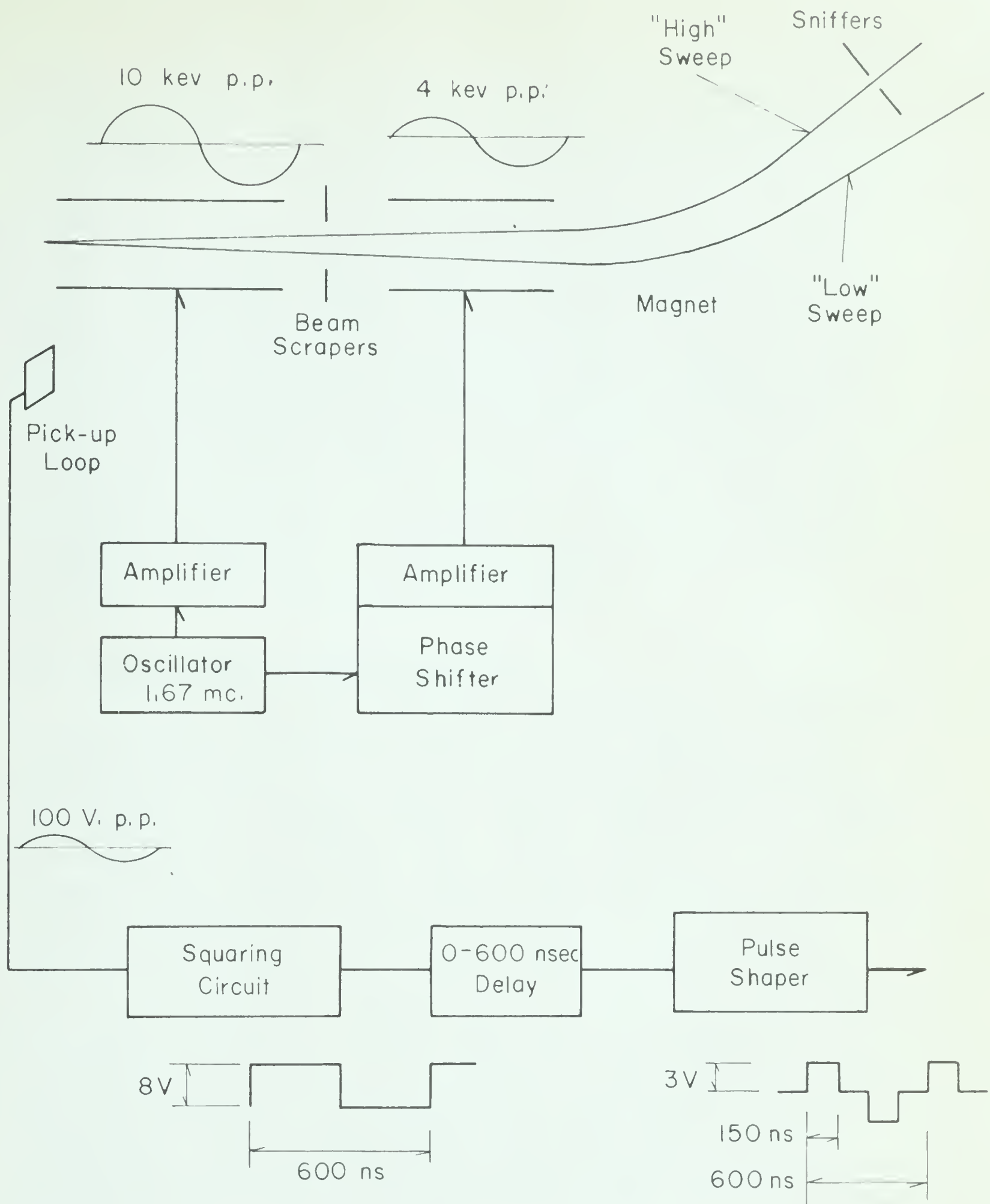


Figure 2-3 A block diagram of the beam pulsing system.

only one of the two current bursts per rf cycle. A variable 0-600 nsec delay (Telcon AS- 48 cable*) allows adjustment of the phase of the start pulse to that of the neutron pulse, so that any 150 nsec time span in the 600 nsec cycle period can be examined during a single run.

It is worth noting that, for both coincidence and pulsed beam experiments, the time span covered can easily be changed. However, a longer time span requires longer timing pulses from the neutron and gamma limiting amplifiers, which results in an increased time dispersion, especially at high counting rates. For best resolution, therefore, it is more profitable to shift the time span covered by inserting a delay in the zero-time indicator rather than to lengthen the time span.

II. Spectrometer Time Resolution

Probably the most important criterion in judging the performance of the spectrometer is the time resolution attainable, which is related to the energy resolution by the simple relationship $\Delta E/E = 2\Delta t/t$, where E and t refer to the energy and flight time of the neutron. Given a fixed neutron energy and a fixed time resolution, the only way of improving the energy resolution is to increase the neutron flight path. If the flight path is doubled, so as to double the energy resolution (provided the effect of target thickness can be neglected), the counting rate, governed by the solid angle of the counter, is decreased by a factor of 4. Therefore, good time resolution is essential. Some of the major contributions to time resolution, with an estimate of magnitudes, are as follows.

*Telcon Works, Greenwich, S.E. 10, England

1. Electronic resolution of the time-to-pulse-height converter. This has been measured to be approximately 2×10^{-11} seconds (Ne 60a).
2. Effects due to finite size of the phosphor.
 - (a) Light collection time of 0.8 nsecs for a 9 inch phosphor. The effect of the collection time is reduced by "tilt" (Ne 59).
 - (b) Flight time of the neutron through the phosphor, since scattering events can occur in any portion. The time required for a 1 Mev neutron to pass through the 1-1/2 inch thick phosphor is 2.7 nsecs.
3. Phosphor response. There is a time dispersion of from 10^{-9} to 10^{-10} seconds in the time of arrival of the first photons at the photocathode. This effect is reduced by limiting on small pulses, that is, ideally on the first photon to reach the photocathode.
4. Photo-multiplier transit-time variation. This effect is minimized by utilizing only a small central region of the photocathode, and limiting on very small pulses; i.e. using only the first electrons to reach the anode of the photo-multiplier. The time jitter is approximately 2 nsecs, and constitutes one of the fundamental limitations to improved time resolution. (Ne 59, Ne 60b)
5. Effect of target thickness. Since the incident beam loses energy as it traverses the target, and neutrons can be produced in any portion of the target, the neutron groups are not monoenergetic. The effect is serious (up to several nsecs) when using low energy neutrons and long flight paths.
6. Beam homogeneity, governed by the stabilization of the Van de Graaff. An energy stability of about ± 3 kev is normally expected. Good energy stabilization becomes much more critical when using a pulsed beam, since the zero-time pulses are derived approximately 6 meters before the target; therefore, added to the inhomogeneity of the beam energy at the target is the effect of variation in the flight time of the burst before hitting the target.
7. RF time jitter in the zero-time pulse, when using a pulsed beam. Measurements performed by using a single pulse selector gate (Ne 59) indicate that the relative jitter is approximately 10^{-10} seconds.

8. Beam pulse duration. Even assuming a monoenergetic, paraxial beam, the pulse width obtained is approximately 1 nsec (see Chapter VI).

The contributions from items 1 and 6 can be checked by using pulsers; total contributions from items 1 to 4 can be checked (except for the flight time of the neutron through the phosphor) by using a Na^{22} source, and observing the coincident annihilation radiation. A time resolution of less than 2 nsecs can be easily obtained when using a Na^{22} source. When measuring coincident gamma-neutron spectra, items 4 and 5 contribute, as well as 2(b). When using a pulsed beam, all the items contribute to time spread; for flight paths of the order of 2 meters, and neutron energies well over 1 Mev, a time resolution of less than 3 nsecs can be obtained. In the work described in Chapter IV, the time resolution for 1 Mev neutrons at a flight path of 5.5 meters was 5.5 nsecs. It should be mentioned, also, that there is a change in rise time of the limited pulse depending on the pulse size from the photomultiplier. This effect is particularly significant when dealing with low energy neutrons, when the side channels must be set to accept a broad pulse height.

III. The Beam Deflection System and the Alternate Pulse Eliminator

In the system used the beam was swept by the deflector plates in the same plane as the deflection of the beam in the analyzing magnet. The energy stabilization slits, from which correction signals are fed to the Van de Graaff corona stabilizer circuit, were also the burst-width defining slits. That is, the beam was swept across the slits at the rf frequency of 1.67 mc. However, the time constants of the corona stabilizer circuit were sufficiently long that the energy stabilization was unaffected by the

rf frequency, and since the time averages of the swept current were equal on each side of the slit, the corona stabilizer was unaffected. The system did have the disadvantage that changes in the amplitude or phase of the rf voltage on the APE had the effect of changing the path of the two sweeps through the magnet (see Figure 2-3), and so of altering the beam energy, since the energy stabilization circuit demands that the beam must pass through the slits. Thus, the beam energy would change to compensate for any drift in the sweep path; in effect, the energy was no longer controlled entirely by the magnetic field. Slow energy drifts, almost certainly attributable to changes in the APE, were sometimes observed to occur if the accelerator terminal voltage was not carefully monitored by means of the generating voltmeter, and controlled by the operator.

The effect of the APE on the energy stabilization is, of course, removed by sweeping the beam perpendicular to the beam deflection in the analyzing magnet. However, sweeping the beam in the plane of the magnetic deflection made it very easy to ensure complete rejection of alternate bursts. The apparent energy separation of the two sweeps, caused by the different paths through the magnet, was approximately 80 kev, when using a deuteron beam of from 1.5 to 2.0 Mev. That is, if the beam energy were 1.90 Mev with the APE off, the accelerator would stabilize either at 1.94 Mev ("high sweep") or at 1.86 Mev ("low sweep") with the APE on; thus one sweep was automatically eliminated. The separation of the two sweeps at the energy stabilization slits can be approximately calculated from the relationship

$$\frac{\Delta E}{E} \approx \frac{-2\Delta S}{L \sin\phi \cos\phi}$$

where $L = 366$ cm is the distance from the center of the magnet to the slits, and ϕ is 25° . Then for $E = 1.5$ Mev,

and $\Delta E = 80 \text{ kev}$, $\Delta S = |2.55| \text{ cm}$. For comparison, at a reasonable slit width of 3 mm, the Van de Graaff energy stabilization, ΔE , as given by the same relationship is approximately $\pm 3 \text{ kev}$. That the 2.55 cm sweep separation is of the expected order of magnitude can be checked by using the approximate relationship

$$V_m \approx \frac{300 \Delta s d v_o m}{(-e) \Delta t L}$$

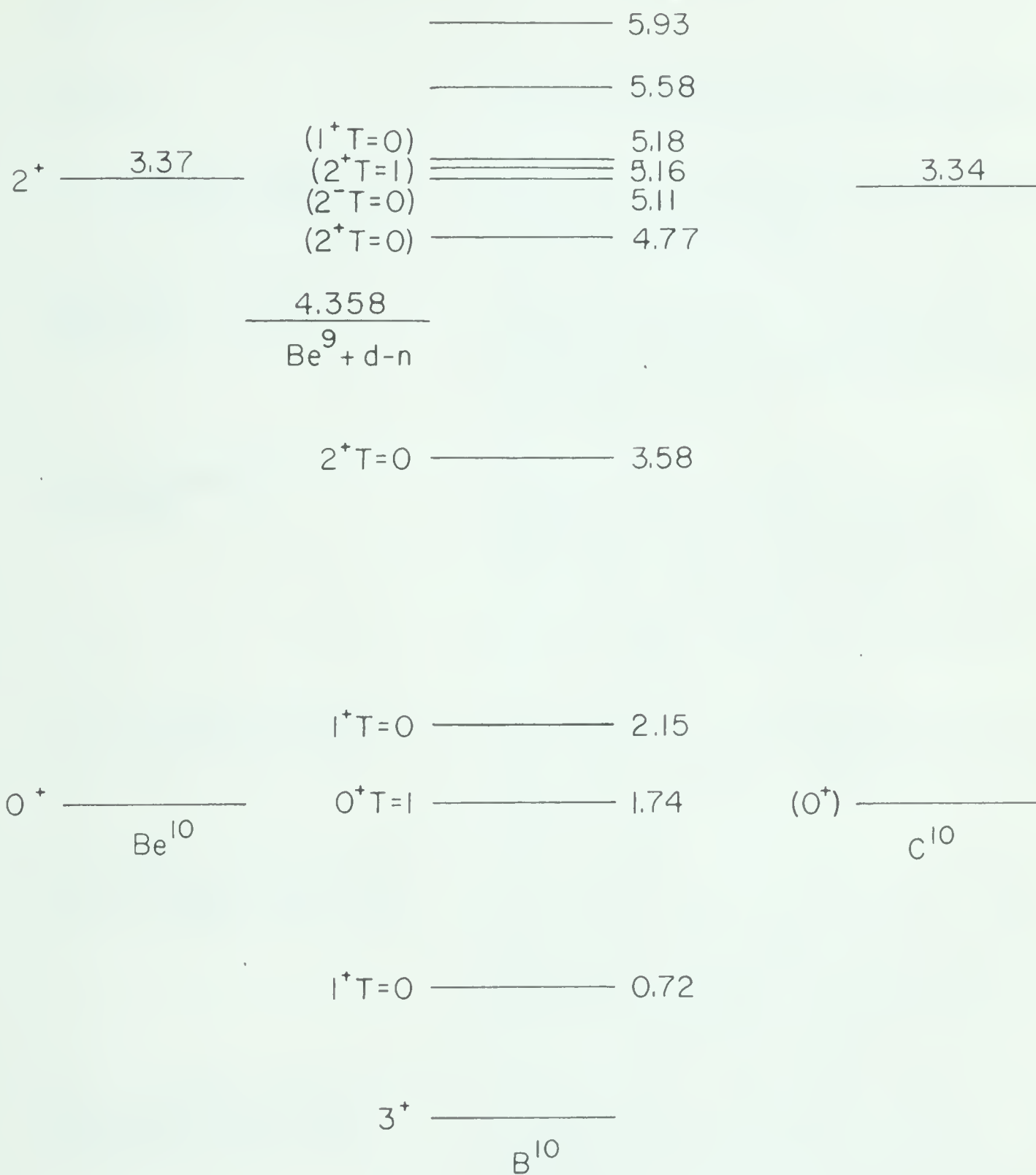
where $d = 1\text{-}1/2 \text{ inches}$. Δt is the time spent in the field of the alternate pulse eliminator plates. For 1.5 Mev deuterons, $\Delta t = 27 \text{ nsecs}$. Then $V_m = 2.1 \text{ kev}$ for the peak-to-peak rf voltage on the alternate pulse eliminator plates, which is a reasonable estimate, although lower than the expected value of nearly 4 kev.

CHAPTER III. THE $\text{Be}^9(\text{d},\text{n})\text{B}^{10}$ REACTION

I. Introduction

This chapter describes time-of-flight measurements on neutrons from the 5.16, 5.11, and 4.77 Mev states of B^{10} produced by the reaction $\text{Be}^9(\text{d},\text{n})\text{B}^{10}$. An energy level diagram for B^{10} , as given in Landolt-Bornstein (La61) is shown in Figure 3-1. The bracketed assignments indicate that there was still some doubt, at least up until 1961, regarding the spins, parities, and isotopic spins of the 4.77, 5.11, and 5.16 Mev levels, even though they have been extensively investigated during the last decade. Previous work concerning these levels is listed in Table 3-1. The last five papers in the table were published after the completion of the present work. As indicated by Table 3-1, Buechner's group at M.I.T. in 1951 (Bu51), confirmed the existence of the first five excited states of B^{10} through inelastic scattering of 7 Mev protons from B^{10} . In 1951, Bonner and Butler (Bo51) showed the existence of the 5.11 and 5.16 Mev levels through a neutron threshold technique. Since then, the states of B^{10} have been studied extensively using the $\text{Be}^9(\text{d},\text{n})\text{B}^{10}$, $\text{Li}^6(\alpha,\gamma)\text{B}^{10}$, and $\text{Be}^9(\text{p},\gamma)\text{B}^{10}$ reactions; widely differing experimental techniques have been employed.

There has been considerable interest in the 4.77, 5.11, and 5.16 Mev levels of B^{10} , because, as was first pointed out by Jones and Wilkinson in 1953 (Jo53), the isotopic spin analog of the first excited states in Be^{10} and C^{10} with $J^\pi = 2^+$, $T = 1$, should be located at an excitation energy of about 5.1 Mev in the self-conjugate nucleus B^{10} . Most information derived from the $\text{Be}^9(\text{d},\text{n})\text{B}^{10}$ and $\text{Li}^6(\alpha,\gamma)\text{B}^{10}$



Energy Levels of B^{10}

Figure 3-1 Energy levels of B^{10} .

Table 3-1

A partial listing of published work concerning the 4.77, 5.11, and 5.16 levels of B^{10} .

<u>Author</u>	<u>Type of Experiment: Conclusions</u>
T. W. Bonner and J. W. Butler (Bo 51)	$Be^9(d,n)$ n-threshold measurements. Confirmed existence of 5.11 and 5.16 levels of B^{10} .
Buechner, <u>et al</u> (Bu 51)	Inelastic scattering of 7 Mev protons from B^{10} . Confirmed the existence of the first five excited states of B^{10} (0.72, 1.74, 2.15, 3.58, and 4.77)
F. Ajzenberg (Aj 52)	$Be^9(d,n)$ $E_d = 3.89$ Mev. Photographic plate work. Neutron spectra at 10° , 45° , and 80° . $l_p = 0$, π^- for at least one of the 5.11, 5.16 doublet. No assignment to 4.77 Mev level, but possibly $l_p = 0$ and $l_p = 2$.
G. A. Jones and D. H. Wilkinson (Jo 53)	$Li^6(\alpha,\gamma)B^{10}$ excitation function. Postulated that 1 member, probably the 5.16, of the 5.11, 5.16 doublet should have $T = 1$.
D. H. Wilkinson and G. A. Jones (Wi 53)	$Li^6(\alpha,\gamma)B^{10}$. Observed 4.77 and 5.16, but not 5.11 states; concluded that 5.11 is likely a 2^- state, and that 5.16 should be the 2^+ , $T = 1$ companion of the 3.77 Mev level in Be^{10} . The 4.77 state is likely (1^+).
G. A. Jones and D. H. Wilkinson (Jo 54)	$Li^6(\alpha,\gamma)B^{10}$. Isotopic spin rule is violated in permitting the formation of the 5.16 Mev state, and operates in inhibiting the $E(1)$ transition from the 5.11 Mev state.
H. Warhanek (Wa 57)	$Li^6(\alpha,\gamma)B^{10}$; 500 kev resonance. Observed gamma angular distributions at 0° , 45° , and 90° . Concluded that the 4.77 Mev level has $J^\pi = 2^+$ or 3^+ .

Table 3-1, continued

<u>Author</u>	<u>Type of Experiment: Conclusions</u>
Meyer-Schutzmeister and Hanna (Me 57)	Angular distribution of gammas resulting from Li^6 plus α . The 5.16 Mev state of B^{10} has $J^\pi = 1^+$ or 2^+ , but does not have $J^\pi = 1^+$, $T = 0$. The results are consistent with $J^\pi = 2^+$, $T = 1$.
T. W. Bonner and C. F. Cook (Bo 54)	$\text{Be}^9(\text{d},\text{n})\text{B}^{10}$ neutron threshold measurements. Concluded from the small relative yield from the 4.77 Mev state that it must have positive parity, since at a low deuteron energy, s-wave neutron emission will then be forbidden.
Neiler, Gibbons, and Good (Ne 57)	Neutron time-of-flight measurements, $E_d = 2$ Mev. 5.11 Mev state of B^{10} formed by s-wave proton capture. Therefore, this level has negative parity.
Sample, Dawson, and Neilson (Sa 58)	$\text{Be}^9(\text{d},\text{n})\text{B}^{10}$ time-of-flight measurements using the coincidence method. 5.16 Mev level of B^{10} is formed by p-wave proton capture at a deuteron energy of 2 Mev.
Neilson, Dawson, Johnson, and Sample (Ne 60)	$\text{Be}^9(\text{d},\text{n})\text{B}^{10}$ time-of-flight measurements using both the coincidence method and a pulsed beam. B^{10} 5.11 has $T = 0$, 5.16 has $T = 1$, $l_p = 1$. Therefore, the 5.16 Mev state has positive parity and possible J values of 0, 1, 2, or 3. The 5.11 Mev state is 10 times more intensely excited than the 5.16 Mev level.
Meyerhoff and Chase (Me 58)	Gamma radiation emitted from deuterons on a thick Be target at $E_d = 2.8$ Mev. For the 5.16 Mev level the results are consistent with an assignment of $J^\pi = 2^+$. For the 5.11 Mev level, $J^\pi = 2^-$.
Meyerhoff, Tanner, and Hudson (Me 59)	$\text{Be}^9(\text{p},\gamma)\text{B}^{10}$ coincident gamma-ray work. Examined gamma cascades through the 5.16 Mev level. $J^\pi = 2^-$, $T = 0$ for the 5.16 level. $J^\pi = 2^+$, $T = 1$ for the 4.77 level.

Table 3-1, continued

<u>Author</u>	<u>Type of Experiment: Conclusions</u>
Tanner and Hanna (Ta 61)	$\text{Be}^9(\text{p},\gamma)\text{B}^{10}$. Gamma coincidence work. 5.16 level has $J = 1$. Tentatively, $J^\pi = 1^+$, $T = 0$. $J^\pi = 0^+$ for the 4.77 Mev level.
Sprenkel and Daughtry (Sp 61a)	$\text{Be}^9(\text{p},\gamma)\text{B}^{10}$. Observed that 2.40 Mev gammas feeding 5.16 level have an observable energy spread. Postulated doublet states in B^{10} at 5.16 Mev.
Sprenkel, Olness, and Segel (Sp 61b)	$\text{Li}^6(\alpha,\gamma)\text{B}^{10}$. Observed a broad (200 kev width) state at 5.18 Mev in B^{10} , for which $\Gamma_\gamma/\Gamma \simeq 3 \times 10^{-7}$. Concluded that 5.18 has $J = 1$, $T = 0$. 5.16 can then have $J^\pi = 2^+$, $T = 1$.
B. H. Armitage and R. E. Meads (Ar 62a)	$\text{B}^{10}(\text{d},\text{d}')\text{B}^{10}$ reaction at a deuteron energy of 10.58 Mev. Observed evidence for the 5.18 Mev level in B^{10} . Did not observe the 5.16 Mev level.
Warburton and Chase (Wa 62)	Gamma-ray threshold measurements in the reaction $\text{Be}^9(\text{d},\text{n},\gamma)\text{B}^{10}$. Were able to show that the 5.16 Mev level is distinct from the 5.18 Mev level observed by Sprenkel, Olness, and Segel. For the 5.16 state, $\Gamma_\gamma = (0.7 \pm 0.35)\Gamma$.
B. H. Armitage and R. E. Meads (Ar 62b)	Through a study of the reactions $\text{B}^{10}(\text{p},\text{p}')\text{B}^{10}$, $\text{B}^{10}(\text{d},\text{d}')\text{B}^{10}$, and $\text{Cl}^{12}(\text{d},\alpha)\text{B}^{10}$ were able to show that the 1.74 Mev and 5.16 Mev states in B^{10} have $T = 1$.
G. Dearnaley and D. S. Gemmel (De 62)	Elastic scattering of alpha-particles by Li^6 . Were able to show that the level in B^{10} at 5.18 Mev is definitely a (1^+) state, with a reduced width of 1.8 Mev.
R. E. Meads and J. E. G. McIldowie (Me 62)	Through a study of gamma-rays from the $\text{Be}^9(\text{p},\gamma)\text{B}^{10}$ reaction, were able to show that the 2.4 Mev transition from the 7.56 Mev state of B^{10} goes to the upper member of the doublet of levels at 5.11 and 5.16 Mev.

reactions has indicated that the 5.16 Mev level is the only likely candidate for the isotopic spin analog. Jones and Wilkinson, for example, in a measurement of the excitation function of the reaction $\text{Li}^6(\alpha, \gamma)\text{B}^{10}$, were able to observe states at 4.77 and 5.16 Mev, but did not observe the 5.11 Mev state (Jo53). They concluded that the 5.11 Mev level was a $J^\pi = 2^-, T = 0$ state, the absence of gamma-rays from the 5.11 Mev level being due to the isotopic spin discouragement of the E1 transition to the ground state. (If it were a 1^- state it could decay to the $J^\pi = 0^+, T = 1$ state at 1.74 Mev.) The 5.16 Mev level was then probably the (2^+) , $T = 1$ companion of the 3.37 Mev level in Be^{10} ; its formation via $\text{Li}^6 + \alpha$ not being a serious violation of the isotopic spin selection rules, since Radicati (Ra53) had calculated that there is approximately 0.25% in intensity of $T = 1$ in the ground state of Li^6 .

Published neutron time-of-flight work (Ne57, Sa58, Ne60) has shown that the 4.77 Mev level in B^{10} is probably a $T = 0$ state, and that the 5.11 level is formed via s-wave protons, while the 5.16 Mev level is formed via p-wave protons. However, neutron groups corresponding to the 5.11 and 5.16 levels have not been simultaneously resolved, although pulsed beam measurements have indicated that the 5.11 level is populated a factor of ten more intensely than the 5.16 Mev level. The 5.16 level assignment was based on measurements using the gamma-coincidence technique; no neutrons coincident with gamma-rays were observed from the 5.11 Mev level.

However, until recently, results from the $\text{Be}^9(p, \gamma)\text{B}^{10}$ reaction indicated that the 5.16 Mev level is not a $J^\pi = 2^+, T = 1$ state. Tanner and Hanna (Ta61) showed that the B^{10} 7.56 Mev level formed by 1.08 Mev protons incident upon Be^9 has $J^\pi = 0^+$; the isotopic spin of this level has been shown to be $T = 1$ (Wa59). This level was also shown to decay by a strong 2.4 Mev gamma-ray to a level near 5.16 Mev. This 2.4 Mev transition was almost certainly magnetic

dipole, for which $T = 1$ from Morpurgo's rule (Mo 58). Thus, an assignment of $J = 1$, $T = 0$ for the 5.16 Mev state in B^{10} was indicated. This dilemma has been recently resolved by Sprenkel, Olness, and Segel through identification of another level in B^{10} centered at 5.18 Mev, and having $J = 1$, $T = 0$ (Sp 61b).

Because of the discrepancies concerning the 5.16 Mev level in B^{10} , and because previous neutron time-of-flight work had failed to resolve the 5.11 and 5.16 Mev levels, it was thought worthwhile to investigate these levels under high resolution conditions. A search was also made for the broad 5.18 Mev level reported by Sprenkel, Olness, and Segel.

Several papers have been published on the 5.16 and 5.18 Mev states in B^{10} after the completion of the experimental work described in this chapter. In the first of these, Warburton and Chase (Wa 62), through measurement of the gamma-rays from the B^{10} 5.16 Mev level near the (d,n) threshold, establish conclusively that the gamma-emitting state near 5.2 Mev in B^{10} is the 5.16 Mev state observed in $Be^9(d,n)B^{10}$ work. The partial gamma-ray width of this state was determined to be $\Gamma/\Gamma_\gamma = 0.7 \pm .35$ from a measurement of the (d,n) and (d,n γ) cross sections. A lower limit to the partial gamma-ray width for decay to the 2.15 Mev level in B^{10} of $\Gamma_{\gamma 3.01} > 0.06\Gamma$ was set; this compares with the result $\Gamma_{\gamma 3.01} < 0.01\Gamma$ obtained by Sprenkel and Daughtry in the study of the gamma-ray spectrum in coincidence with the 2.40 Mev gamma-ray emitted by the 7.56 Mev level in B^{10} . Therefore, the 2.40 Mev gamma-ray emitted by the 7.56 Mev level must be a transition to another state near 5.2 Mev in the B^{10} , presumably the 5.18 Mev level. Further, Warburton and Chase point out that, on the basis of calculations by True and Warburton (Tr 61), it is quite possible that the 5.18 Mev state of B^{10} belongs to a doubly excited configuration

and would therefore not be excited by single nucleon direct interactions such as inelastic scattering, stripping, or pick-up, but could be excited, for example, by the $C^{12}(d,\alpha)B^{10}$ reaction. Armitage and Meads (Ar 62a) describe evidence for the broad 5.18 Mev state in B^{10} in a study of the $B^{10}(d,d')B^{10}$ reaction at a deuteron energy of 10.58 Mev. The width of the 5.18 Mev state was estimated to be 130 ± 30 kev.

In a second recent paper Armitage and Meads (Ar 62b), in a study of the reactions $B^{10}(p,p')B^{10}$, $B^{10}(d,d')B^{10}$, and $C^{12}(d,\alpha)B^{10}$ observed that the 1.74 and 5.16 Mev levels were both excited by proton inelastic scattering, but not by deuteron inelastic scattering, indicating that $T = 1$ for these states. The 1.74 and 5.16 Mev states were also found not to be excited by the reaction $C^{12}(d,\alpha)B^{10}$ further confirming the $T = 1$ assignment for these levels. Both the deuteron and the alpha-particle have $T = 0$. Therefore, it should not be possible to excite $T = 1$ states by deuteron inelastic scattering or by $C^{12}(d,\alpha)B^{10}$ reaction.

Finally, Dearnaley and Gemmel (De 62), in a study of elastic scattering of alpha-particles by Li^6 , report that the level in B^{10} at 5.18 Mev is definitely (1^+) , with a reduced width of 1.8 Mev.

II. Experimental: Angular Distribution Measurements

(a) General Experimental Arrangement

The general experimental arrangement has been described by Neilson et al (Ne 60). Sources of background caused by the beam hitting obstructions and neutron scattering have been reduced as much as possible. The Van de Graaff, the beam deflector and scraper slits, and the analysing magnet are all contained in a room surrounded by 24 inch thick concrete walls. The drift tube is encased by a one inch thick lead sheath from the point where it emerges from the

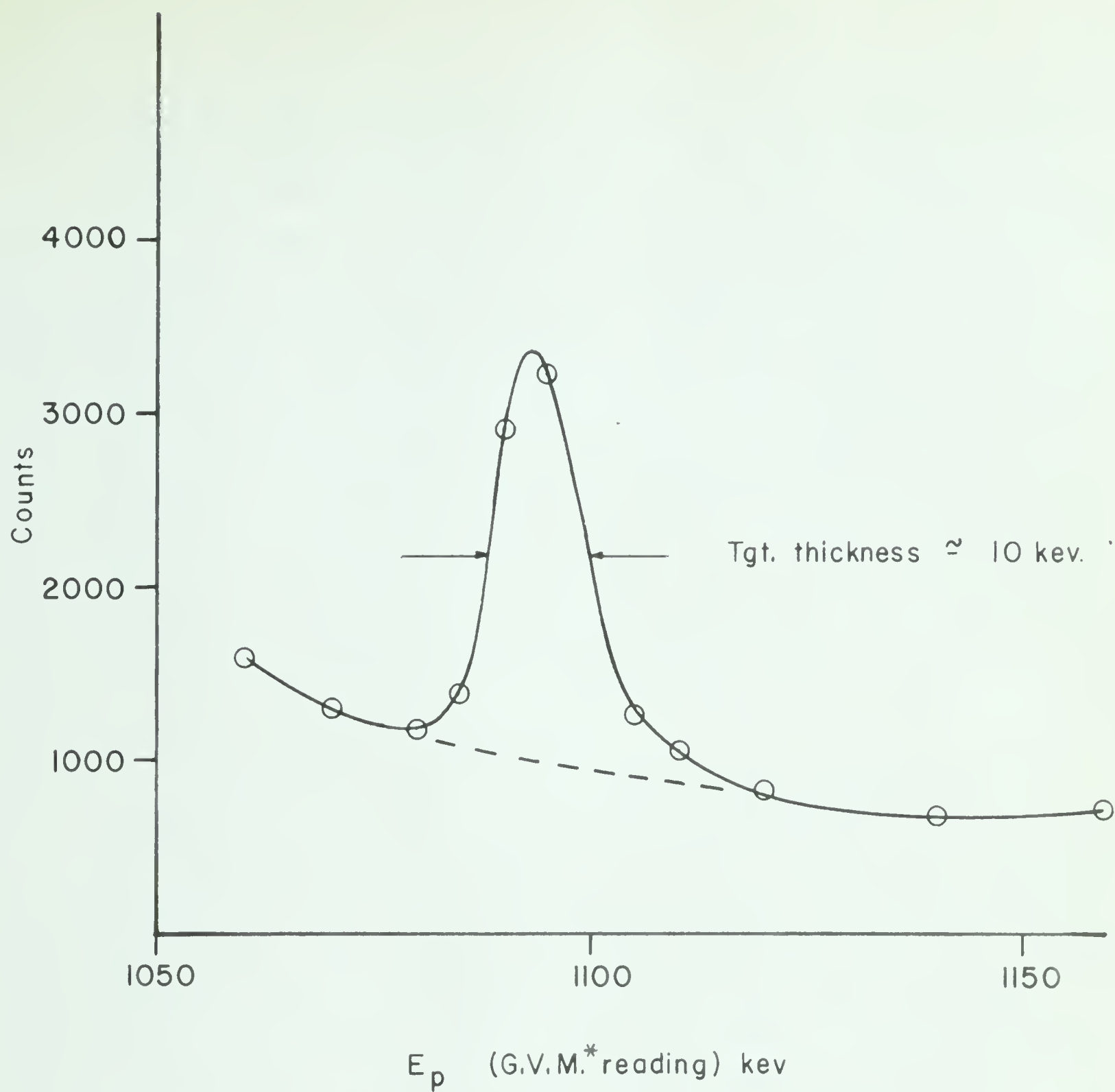


Figure 3-2 Measurement of the beryllium target thickness at the 1.084 Mev resonance of $\text{Be}^9(p,\gamma)\text{B}^{10}$.

*Generating Voltmeter

concrete wall to within one meter of the target; additional lead is placed around the carbon trap, the energy stabilization slits, and the retractable viewer. Neutrons produced at the carbon trap and at the slits are further attenuated by means of four inches of a paraffin-lithium carbonate mixture surrounding the lead. For the reduction of neutron scattering, the target room is of light frame construction, and has a pit about 15 feet square and 7 feet deep under the light metal floor at the target position. In an attempt to minimize background due to carbon and deuterium build-up, before the present work was begun, the energy sensing slits were replaced, the carbon trap and the end section of the beam pipe were cleaned, and the target chamber was relined with clean silver foil.

(b) Target Preparation

Beryllium targets were prepared by evaporating beryllium metal onto a 0.001 inch thick platinum sheet, which had been previously cleaned in a hot chromic acid cleaning solution, rinsed off in distilled water, and dried under a heat lamp. The chromic acid was prepared from fresh chemical reagents, and, to prevent contamination, was discarded after each usage. Targets were weighed before and after evaporation. To ensure reasonable target uniformity, the platinum foils were placed in the evaporator at a distance of approximately three inches from the filament. The filaments, 0.005 inches thick molybdenum, were cleaned in a similar manner to the platinum before use. Prepared targets were checked for the presence of C^{12} contamination by bombarding them with deuterons for several minutes, and looking for the characteristic 0.51 Mev, 10 minute half-life, gamma radiation from the build up of N^{13} . Freshly prepared targets were found to be virtually free from carbon contamination; however, after several hours deuteron bombardment, carbon build-up on the target did become significant.

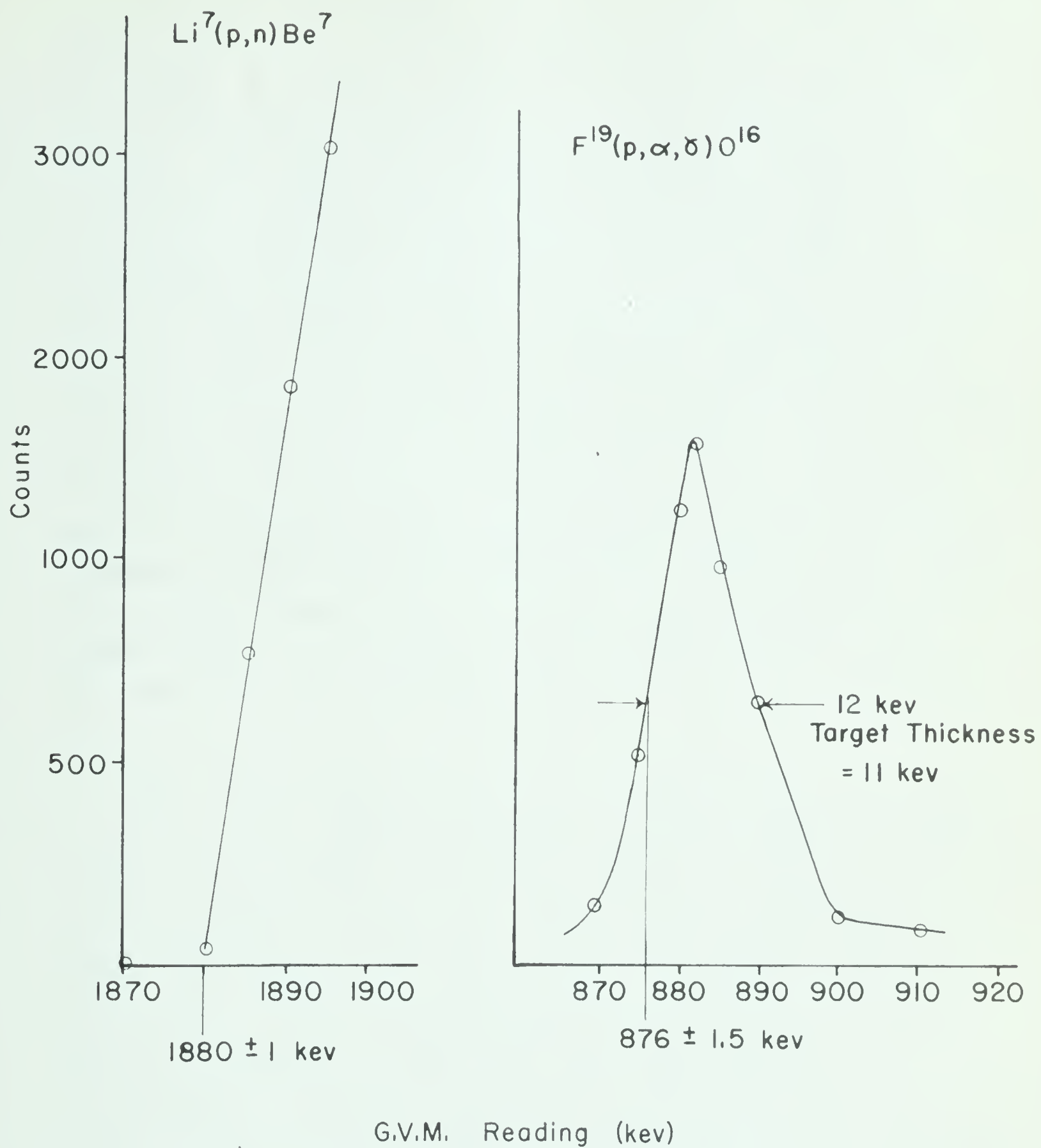


Figure 3-3 Generating voltmeter calibration using the 1880.7 kev $\text{Li}^7(p,n)\text{Be}^7$ threshold and the 872.5 resonance in $\text{F}^{19}(p,\alpha,\gamma)\text{O}^{16}$.

To resolve the 5.11 and 5.16 levels of B^{10} it was necessary to use a target thin in comparison with the separation of the two levels (about 50 kev) in order that the spread in neutron energy due to the target thickness would not prevent resolution of the two neutron groups. However, the target had to be sufficiently thick to give reasonable counting rates at relatively large neutron counter distances. For the high resolution work, a target of $50 \mu\text{gm}/\text{cm}^2$ was used; where it was not necessary to resolve the 5.11 and 5.16 Mev levels, a $200 \mu\text{gm}/\text{cm}^2$ target was used in order to benefit from higher counting rates. At counter distances of greater than 2.5 meters, the resolution obtainable with the $200 \mu\text{gm}/\text{cm}^2$ target became steadily worse than the resolution obtainable with the $50 \mu\text{gm}/\text{cm}^2$ target. The target thickness of the $50 \mu\text{gm}/\text{cm}^2$ target, as measured by the 1.084 Mev $\text{Be}^9(p,\gamma)\text{B}^{10}$ resonance, was found to be approximately 10 kev for the 1 Mev protons (see Figure 3-2). A 4 inch by 4 inch collimated NaI crystal was used to detect the gamma-rays.

(c) Generating Voltmeter Calibration

The Van de Graaff generating voltmeter was calibrated using the $\text{Li}^7(p,n)\text{Be}^7$ neutron threshold at 1880.7 kev (Ma 61). A thick lithium target was used; the boron trifluoride neutron monitor was placed at 0° to the incident proton beam. The generating voltmeter was adjusted to read correctly to within approximately ± 1 kev at the neutron threshold energy. A check was then made using the $\text{F}^{19}(p,\alpha,\gamma)\text{O}^{16}$ resonance at 872.5 kev (Ma 61), using an 11 kev thick fluorine target. At this energy the generating voltmeter read 3 kev too high; however, this error was not considered serious.

(d) Angular Distribution Measurements

An approximate check was first made of the energy of neutrons from the 5.11, 5.16 Mev doublet levels of B^{10} by comparing the position on the pulse height analyser of the unresolved doublet line with the position of the neutron line from the 6.48 Mev state of C^{11} . The 6.48 Mev state of C^{11} was chosen because the reaction Q-value is well known, and is nearly the same as the $Be^9(d,n)B^{10}$ reaction Q-value for excitation of the 5.11 and 5.16 Mev levels of B^{10} (La 61). The flight time obtained for the doublet neutron line agreed exactly with the expected flight time for neutrons from the 5.11 Mev state of B^{10} , indicating that the 5.11 Mev state is the most strongly fed member of the doublet.

Neutron spectra from the 5.11, 5.16 Mev doublet in B^{10} were recorded at increasing flight paths and at the optimum resolving conditions which could be obtained until it was possible to see clearly the resolved neutron groups from the 5.11 and 5.16 Mev states, and to check that their time separation agreed with the expected separation at varying counter distances and angles. A deuteron energy of 1.9 Mev was used. Typical spectra, recorded at flight paths of 2.00 meters, 4.10 meters, and 5.42 meters, all at a counter angle of 20° with respect to the incident beam direction, are shown in Figures 3-4, 3-5, and 3-6, respectively. The time scale for all cases is approximately 1 nsec per channel. The derived spectrum shapes for neutrons from the 5.16 Mev level are shown in Figures 3-5 and 3-6. A comparison spectrum for neutrons from the 6.48 Mev state in C^{11} is shown in Figure 3-7. At 4.1 meters, neutron groups from the 5.11 and 5.16 Mev levels of B^{10} are partially resolved; however, distribution measurements would be strongly dependent on the line shape. At 5.42 meters, the separation of the two neutron groups is sufficient for the analysis of the 5.16 spectrum to be

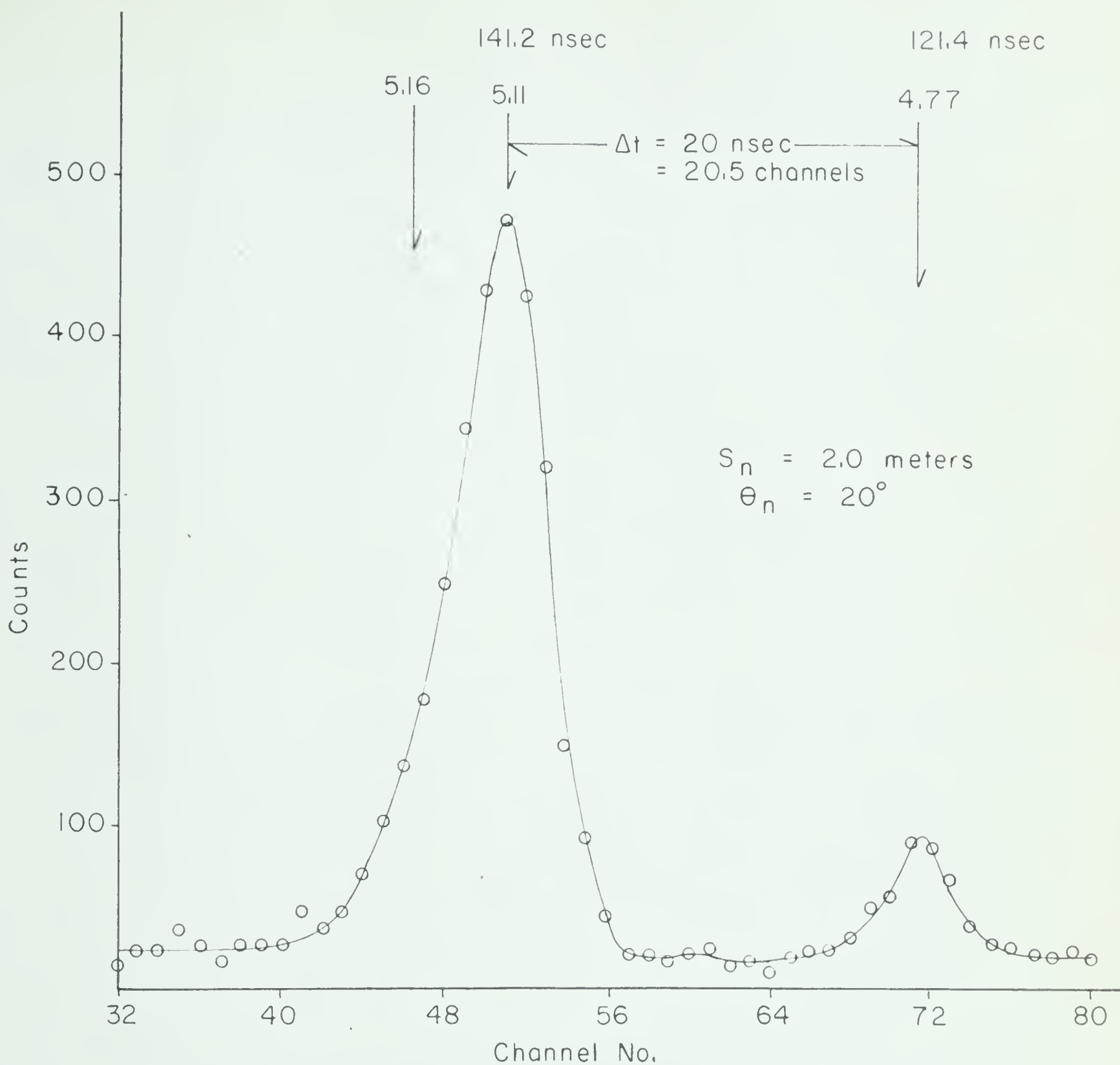


Figure 3-4 $\text{Be}^9(d,n)\text{B}^{10}$. Neutron groups leading to the unresolved 5.11, 5.16 Mev doublet and to the 4.77 Mev level of B^{10} .

$E_d = 1.905 \text{ Mev}$, $10 \mu\text{coulombs}$

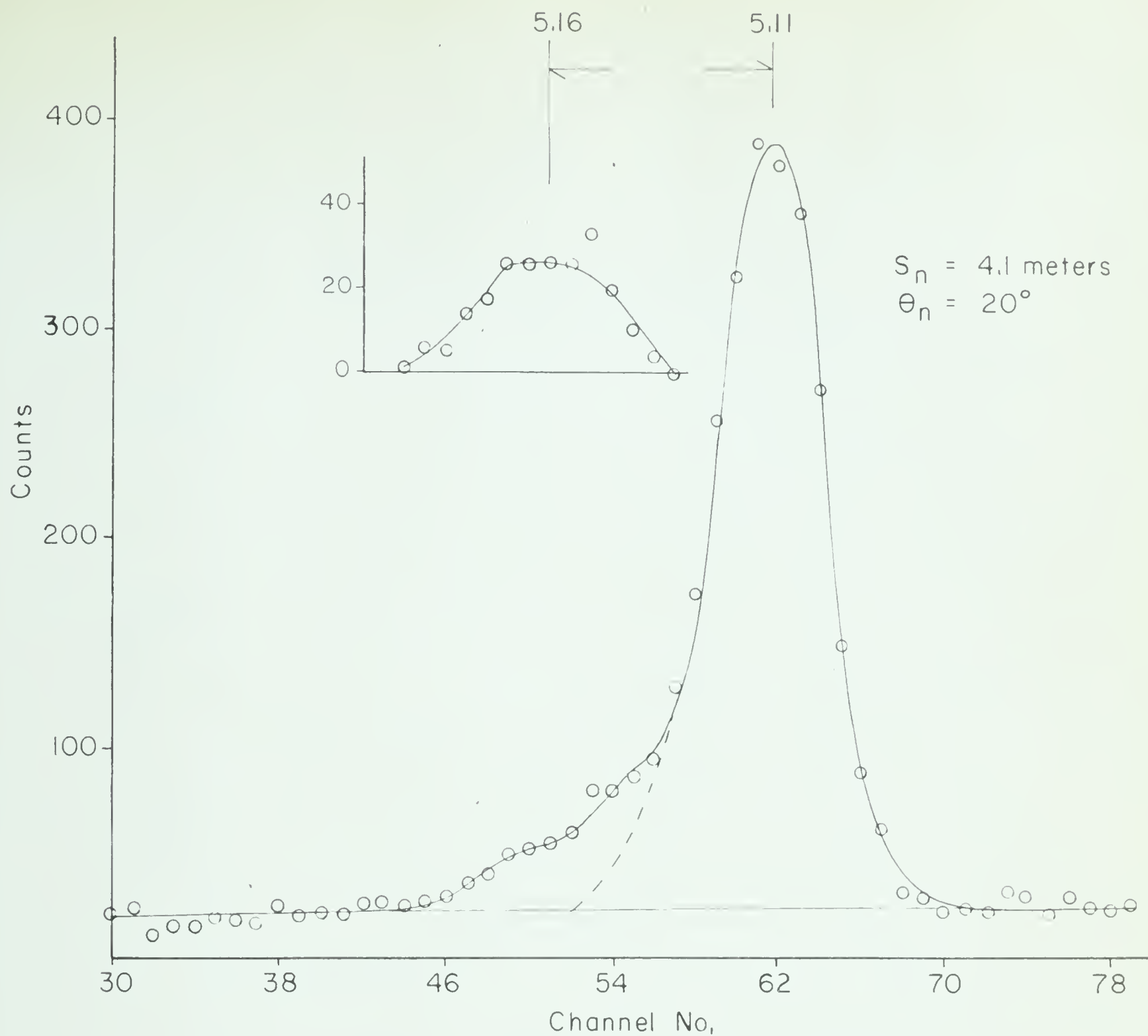


Figure 3-5 $\text{Be}^9(d,n)\text{B}^{10}$. Neutrons leading to the 5.16 and 5.11 Mev levels of B^{10} .

$E_d = 1.905$ Mev, 40 $\mu\text{coulombs}$

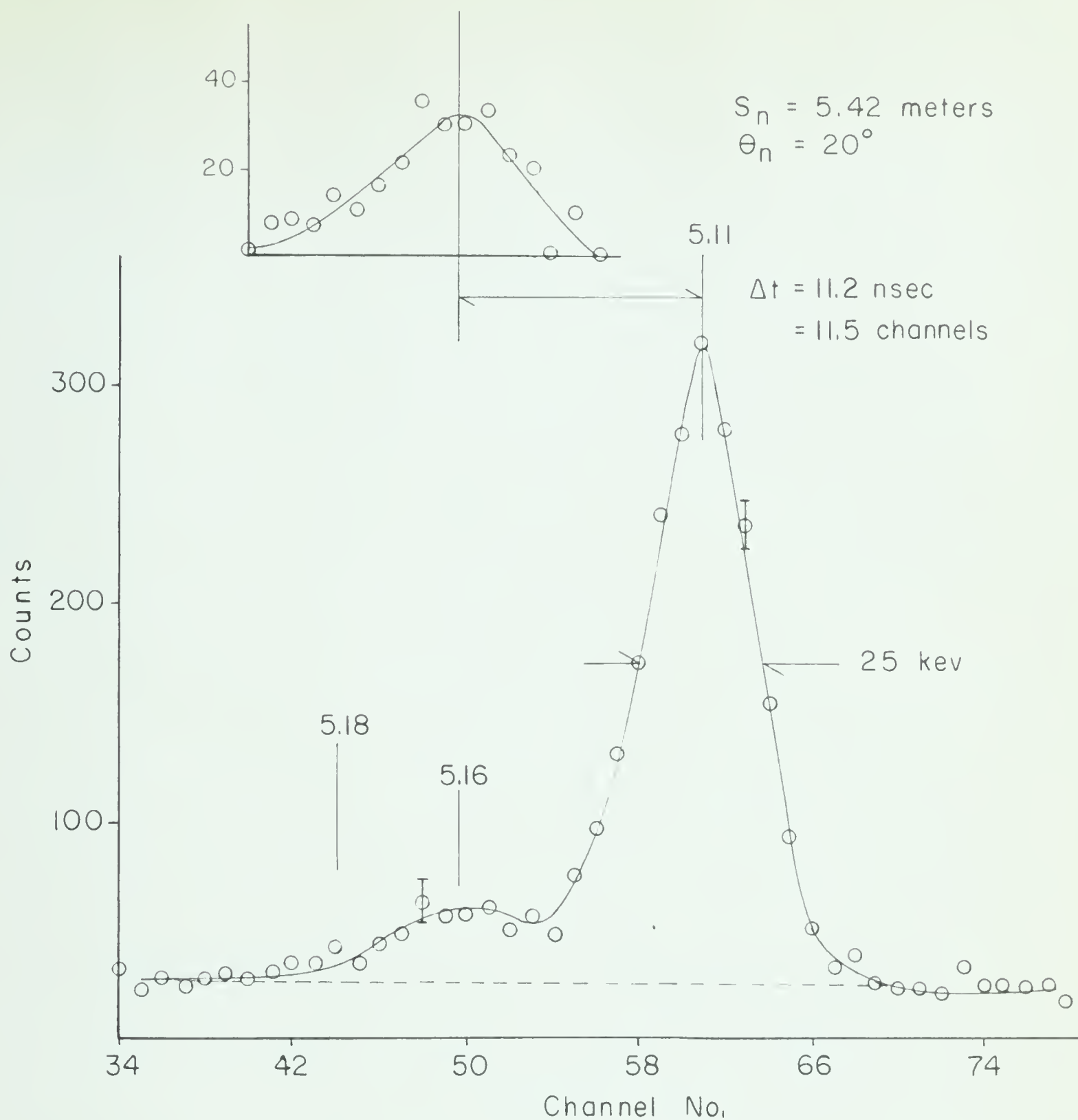


Figure 3-6 $\text{Be}^9(d,n)\text{B}^{10}$. Neutrons leading to the 5.16 and 5.11 Mev levels of B^{10} .

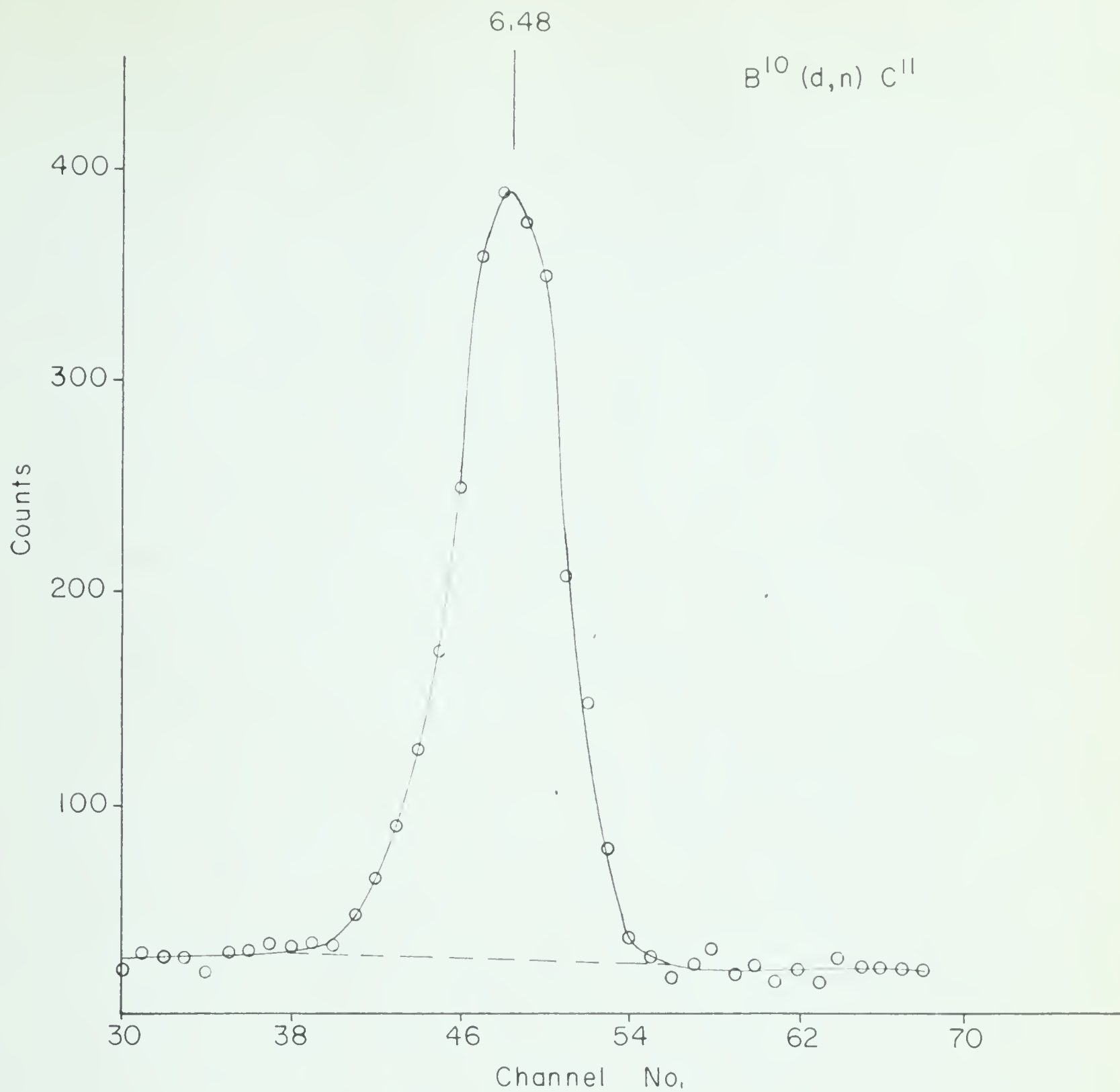


Figure 3-7 $B^{10}(d,n)C^{11}$. Neutrons leading to the 6.48 Mev level of B^{10} .

$E_d = 1.5$ Mev, $\Theta_n = 30^\circ$, $S_n = 3$ meters

reasonably independent of the line shape assigned to the neutron group from the 5.11 Mev level. There is no indication in these spectra of neutrons from the 5.18 Mev level in B^{10} ; the expected peak position of neutrons from this state is indicated in Figure 3-6. If the width of the 5.18 Mev level is 130 kev, the 5.18 spectrum should extend to the mid-point of the 5.11 line. It is interesting to note that at 5.42 meters, the flight time for neutrons from the 5.16 Mev level is nearly 400 nsecs, well over one-half of the rf cycle period of 600 nsecs. The complete rejection of alternate sweeps on the target is therefore necessary in order to avoid background from events produced by alternate half-cycle pulses on the target.

Angular distribution measurements were made of the resolved 5.11, 5.16 spectra at 5° intervals at angles from 0° to 60° in the laboratory system. All runs were carried out at a deuteron bombarding energy of approximately 1.91 Mev. Typical spectra, recorded at laboratory angles of 5° , 30° , and 60° , are shown in Figure 3-8. It was not possible to resolve the two neutron groups at counter angles greater than 60° , partly because of the decrease in intensity of both neutron groups with increasing angle, and partly because of the decrease in efficiency of the neutron counter for lower energy neutrons. The neutron bias used in this work was approximately 600 kev.

The energies of the 5.11 and 5.16 neutron groups at a deuteron energy of 1.9 Mev, and the corresponding flight times for 5 meters, are shown in Figure 3-9 as a function of angle. Between 0° and 60° , the energy of neutrons from the 5.16 Mev level decreases from 1 Mev to 800 kev. However, as the neutron energy decreases, the time separation between the 5.11 and 5.16 neutron groups for a given flight path increases. Thus, at 60° the time separation of the two groups for a flight path of 3 meters is 7.5 nsecs; at 0° a counter distance of 3.8 meters is required for a

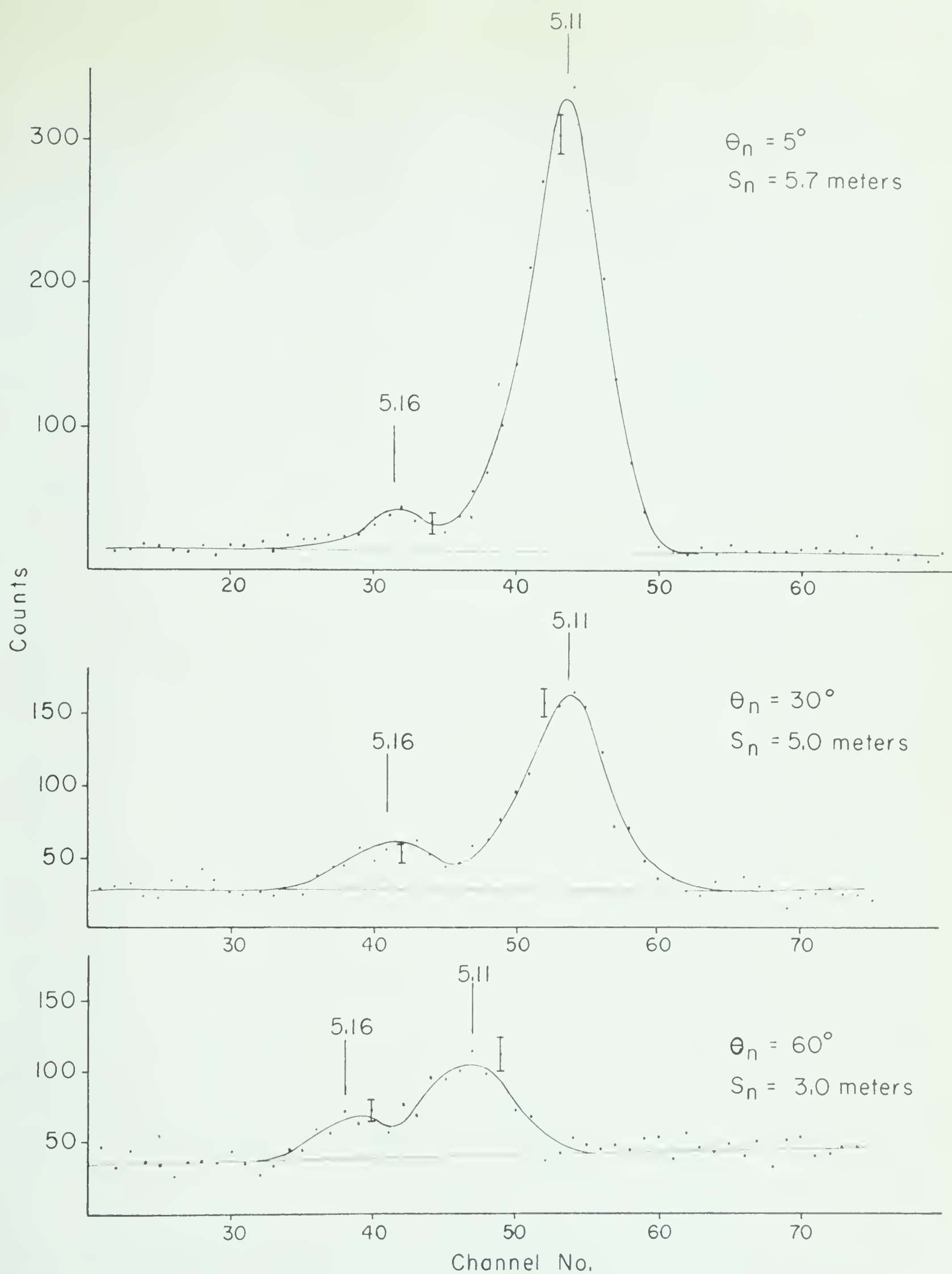


Figure 3-8 $\text{Be}^9(d,n)\text{B}^{10}$. Neutrons leading to the 5.11 and 5.16 Mev levels of B^{10} .

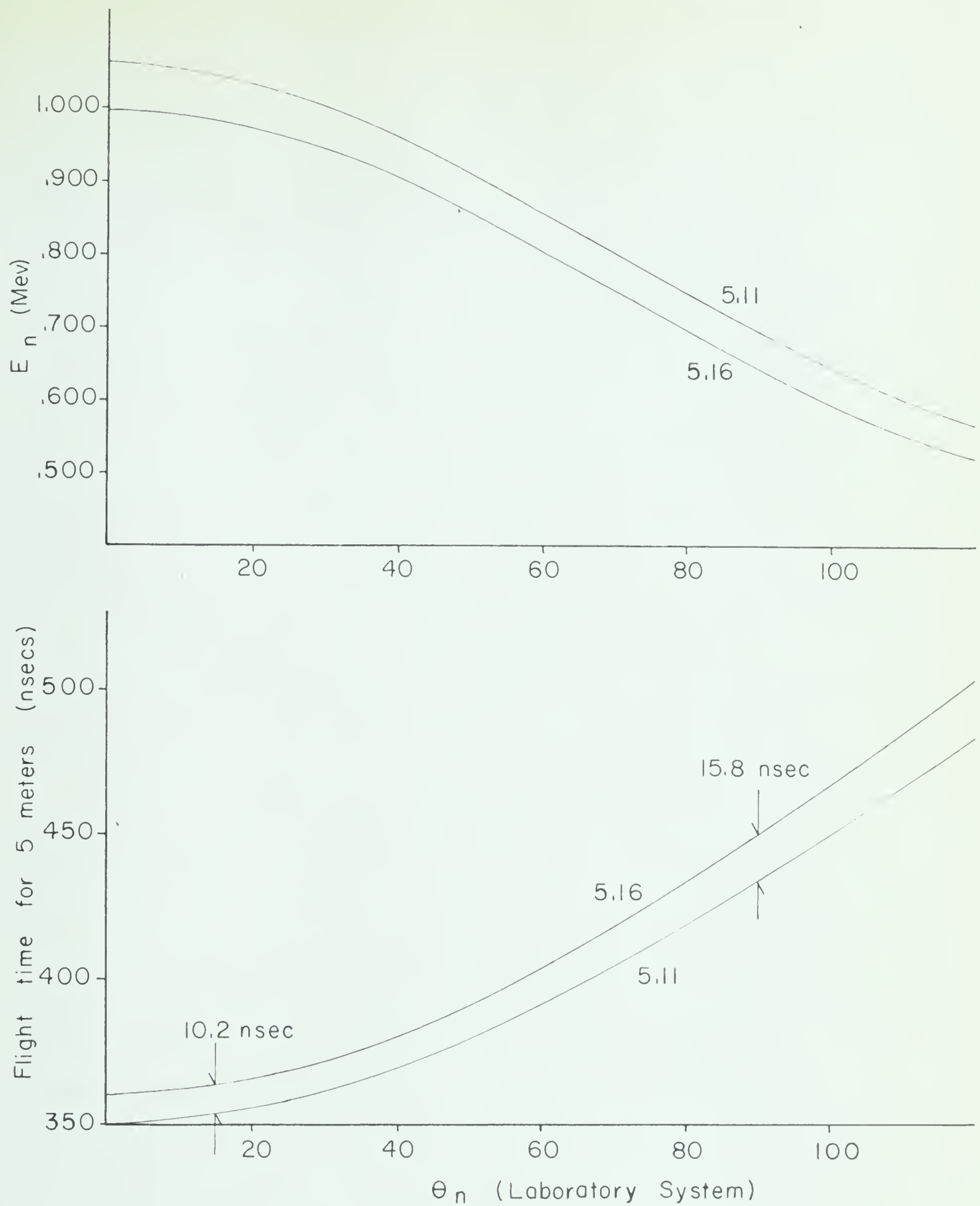


Figure 3-9 Energies and flight times for neutrons to the 5.11 and 5.16 Mev levels of B^{10} produced in the reaction $Be^9(d,n)B^{10}$. $E_d = 1.9$ Mev.

time separation of 7.5 nsecs. Moreover, since the relative intensities of the two groups become more nearly equal at larger angles, it becomes less difficult to resolve the 5.16 even at a fixed time separation. The flight path was, therefore, not kept fixed, but was decreased with increasing angle, in order to maintain a reasonable true-to-chance counting rate and still resolve the 5.11 and 5.16 groups. At 0° a counter distance of 5.63 meters was used; at 60° the flight path was reduced to 3 meters. The data were normalized to an integrated target current of 40 μ coulombs and a flight path of 5 meters, and were corrected for the changes in efficiency of the neutron detector with neutron energy. Graphs of the resulting angular distribution data are shown in Figure 3-10. The corrections for the variation in efficiency of the detector with neutron energy were obtained from the $T(p,n)\text{He}^3$ reaction. The experimental data are given in Appendix II. As indicated by the graphs, the ratio of the 5.11 to 5.16 intensity decreases from $15.5 \pm 3 : 1$ at 0° to $2.3 \pm .5 : 1$ at 60° .

Angular distribution measurements were then made at angles up to 135° in the laboratory system of neutrons leading to the unresolved 5.11, 5.16 Mev doublet states, and to the 4.77 Mev state of B^{10} . The incident deuteron energy was 1.91 Mev. The flight path was fixed at 1.50 meters. A clean "thick" 200 $\mu\text{gm}/\text{cm}^2$ target was used, since it gave higher true-to-chance neutron counting ratios at large angles than did the "thin" 50 $\mu\text{gm}/\text{cm}^2$ target. Angular distribution measurements on neutrons leading to the 4.77 Mev level were repeated at a deuteron energy of 1.50 Mev.

The angular distribution data are given in Appendix II. The normalized data for the unresolved 5.11, 5.16 doublet are shown plotted in Figure 3-11. The same graph shows the distributions, given previously in Figure 3-10, for the resolved 5.11 and 5.16 Mev levels. The graphs showing

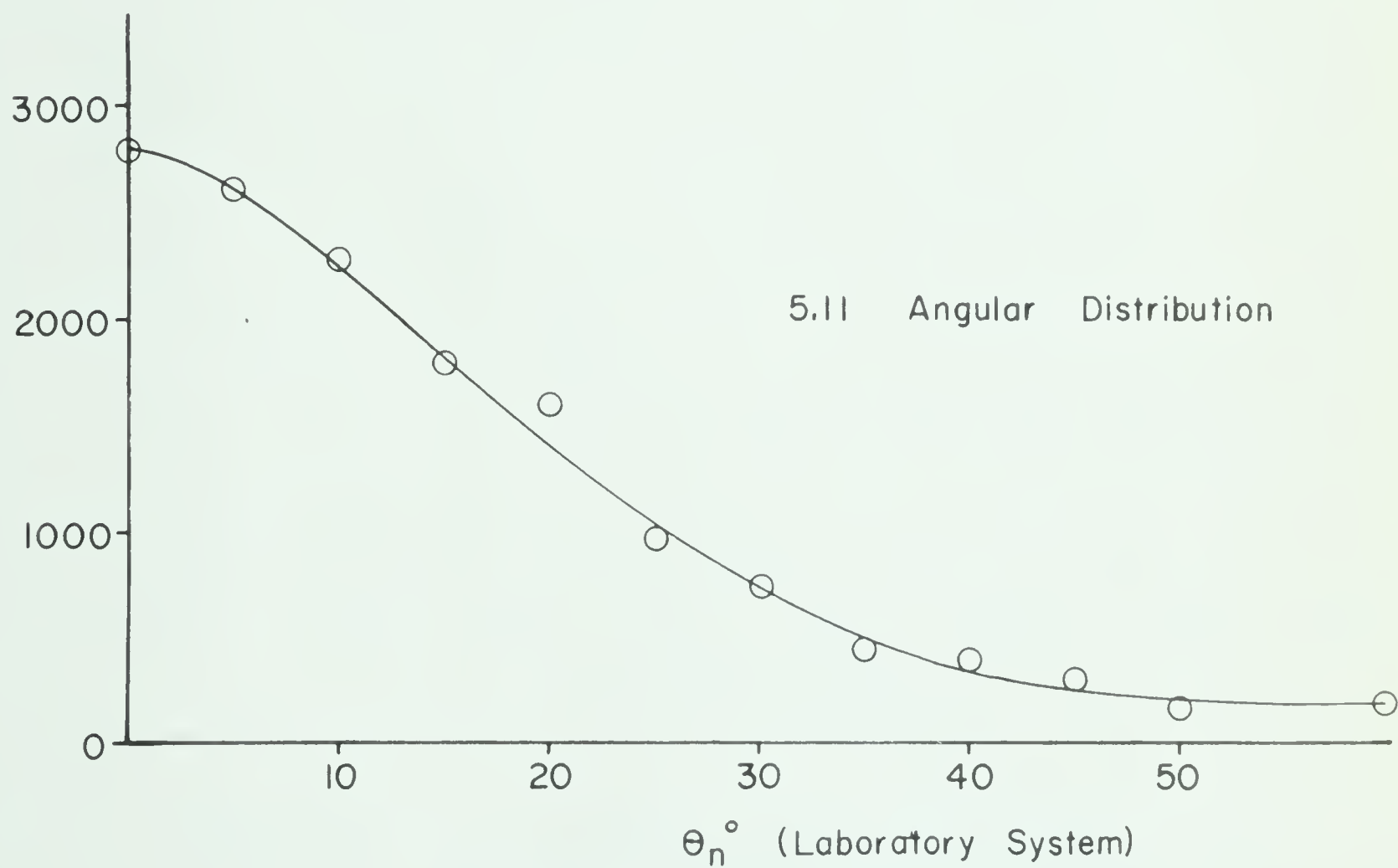
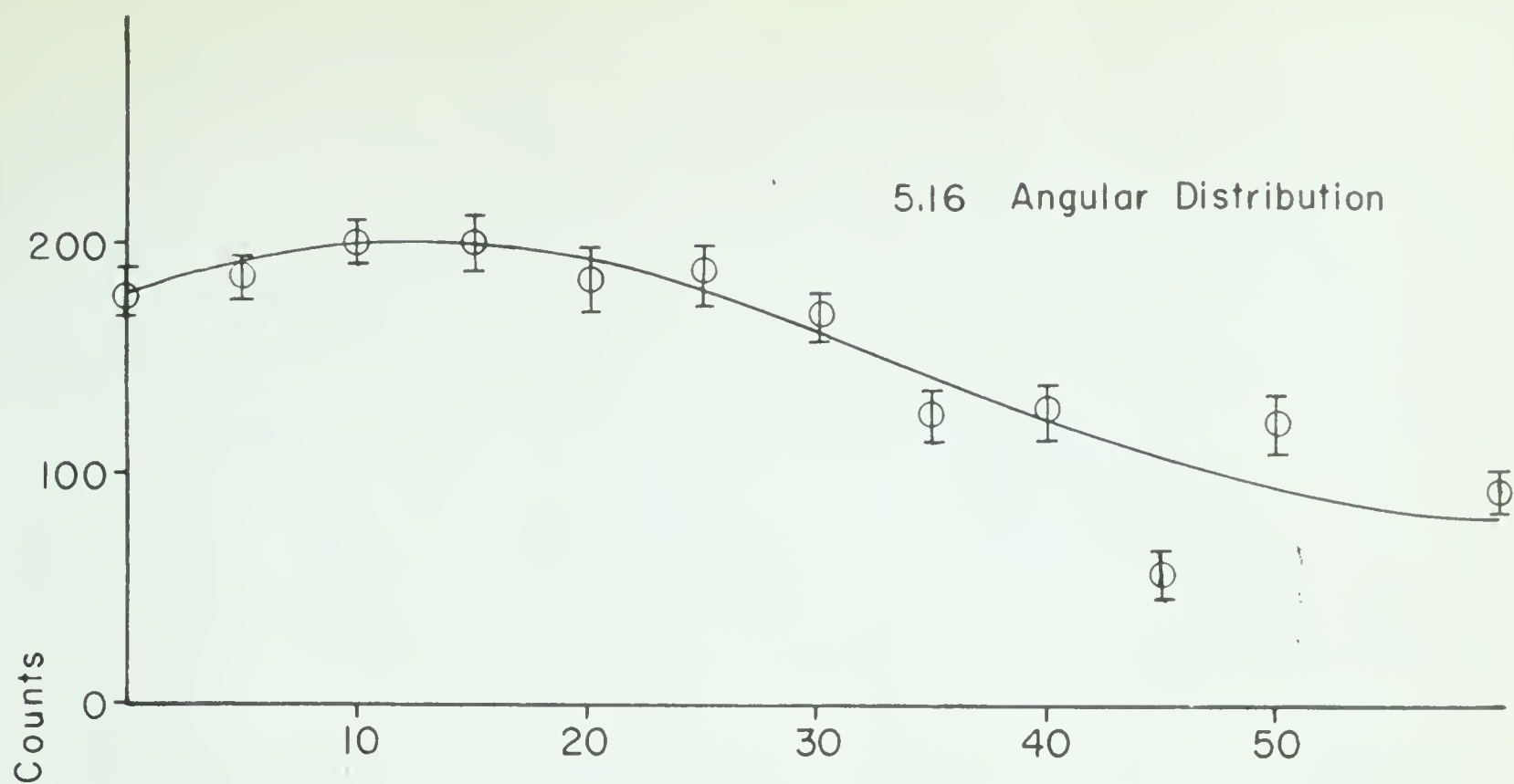


Figure 3-10 $\text{Be}^9(d,n)\text{B}^{10}$. Angular distribution data for neutrons to the 5.11 and 5.16 Mev levels of B^{10} . $E_d = 1.9$ Mev.

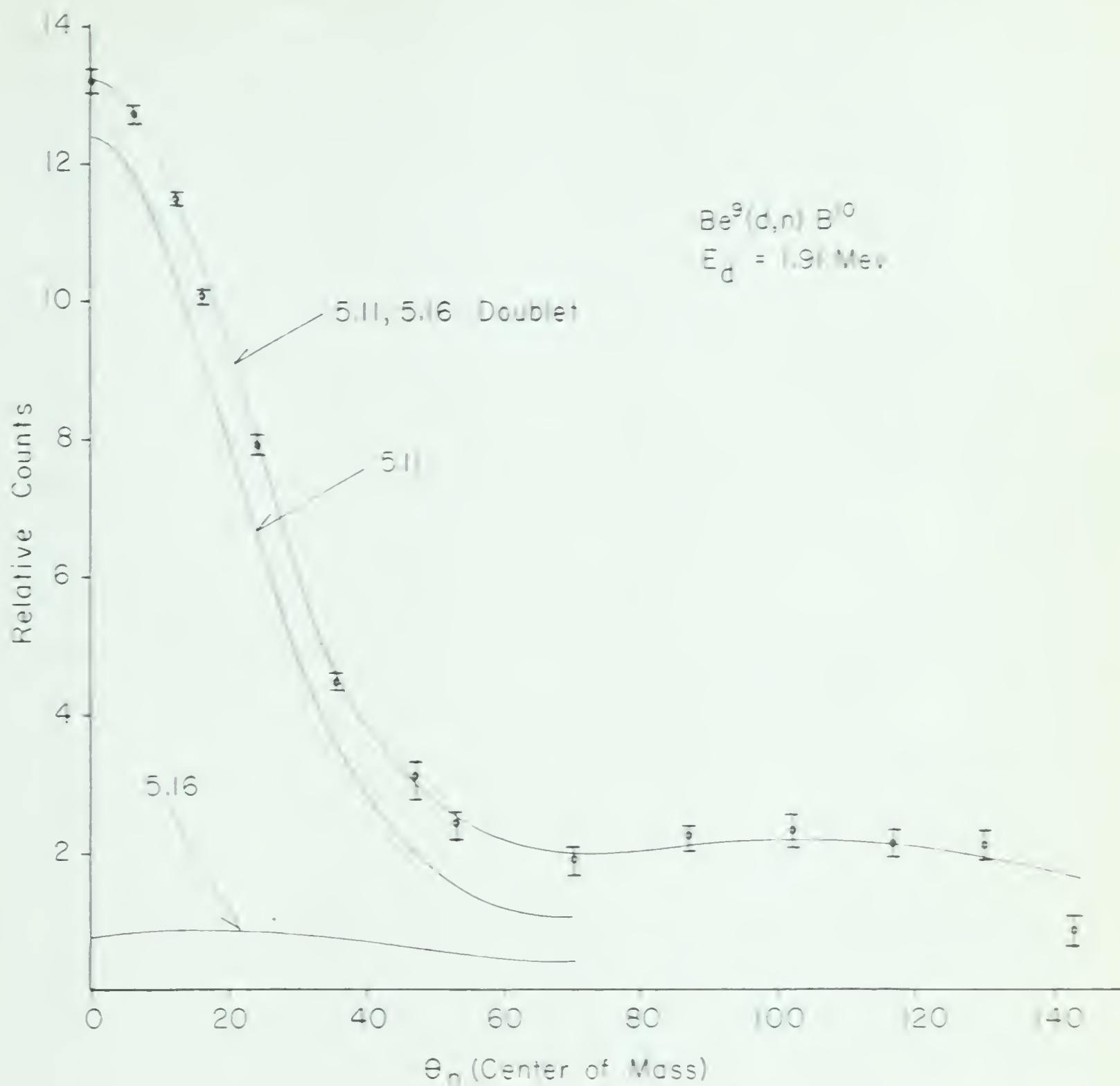


Figure 3-11 Be⁹(d,n)B¹⁰. Angular distributions for neutrons leading to the unresolved 5.11, 5.16 doublet states of B¹⁰.

the resolved distributions have been "normalized" at 0° ; within experimental error the sum of the resolved distributions agrees with the doublet angular distribution between 0° and 70° . The normalized data for the 4.77 angular distributions are plotted in Figure 3-14. The shape of the distribution observed at 1.5 Mev agrees closely with the shape observed at 1.9 Mev.

The gamma eliminator circuit does not discriminate well between neutrons and gamma-rays for neutron energies less than 1 Mev; therefore, as the neutron energy decreased, it became necessary to lower the bias setting of the gamma-ray eliminator circuit. This, of course, allowed a higher background due to gamma-rays and low energy "degraded" neutrons, and also changed the efficiency of the neutron counter (see Appendix II). At back angles, as the neutron counter approached the carbon trap and adjacent energy defining slits, an extraneous peak appeared in the neutron spectrum. This peak was shown to be caused mostly by low energy neutrons from the vicinity of the slits, and was eliminated by positioning lead and wax shielding between the slits and the neutron counter.

A check was made for the presence of C^{12} contamination in the $200 \mu\text{gm}/\text{cm}^2$ beryllium target immediately after the distribution measurements, since at the counter distance used (1.5 meters) neutrons from $C^{12}(d,n)N^{13}$ ($Q = -0.281$ Mev) would not be resolved from neutrons from the 4.77 Mev level of B^{10} ($Q = -0.41$ Mev). The 4.77 Mev data would, therefore, include contributions from $C^{12}(d,n)N^{13}$. However, measurement revealed an insignificant build-up of 10 minute half-life activity from the vicinity of the target. A further check was made by comparing the neutron spectrum from the target used in the angular distribution measurements to the neutron spectrum from a "dirty" beryllium target which had been bombarded for long periods of time at high beam currents. The counter was placed at an angle

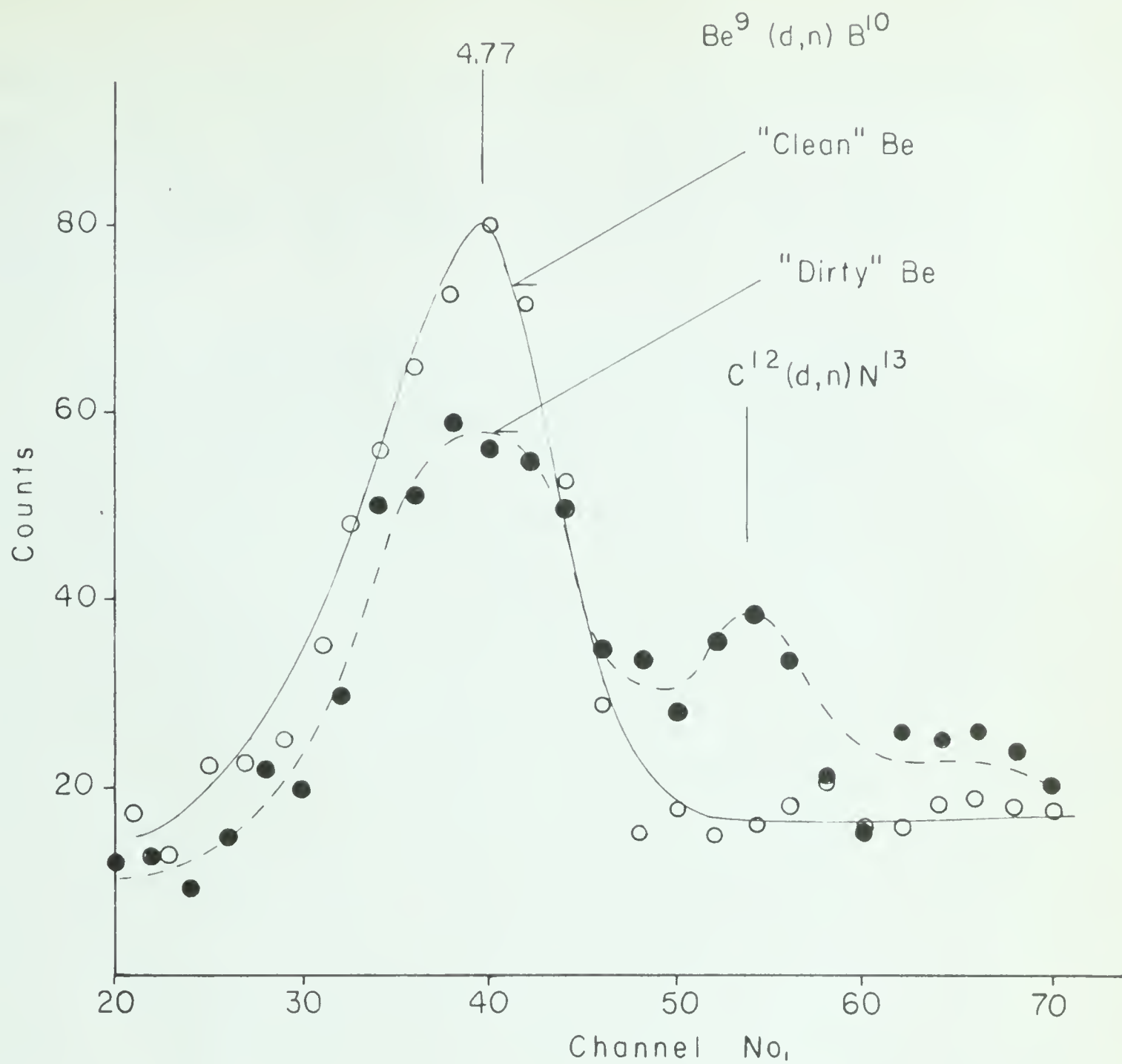


Figure 3-12 $Be^9(d,n)B^{10}$. Neutron spectra from "clean" and "dirty" beryllium targets. $E_d = 1.5$ Mev.

of 20° , two meters from the target. The deuteron energy was 1.5 Mev. The absence of the contaminant peak in the spectrum from the "clean" target clearly indicates the relative absence of carbon. The spectra are shown in Figure 3-12.

(e) A Search for the 5.18 Mev Level in B^{10}

An unsuccessful attempt was made to observe the broad state centered at 5.18 Mev in B^{10} first reported by Sprenkel, Olness, and Segel (Sp 61), and later confirmed by Armitage and Meads (Ar 62a). Proton capture to this state should result in an observed neutron spectrum with an energy spread of approximately 130 kev; the neutron spectra leading to the 5.11 and 5.16 Mev states would then be expected to be sitting above a broad spectrum caused by neutrons leading to the 5.18 Mev state. $Be^9(d,n)B^{10}$ spectra were recorded using the thick beryllium target and a 2 meter flight path. The deuteron energy was 1.91 Mev; spectra were recorded at counter angles of 5° and 30° . No evidence was observed for neutrons from the 5.18 Mev state. The amplitude of the spectrum line produced by neutrons leading to the 5.18 Mev state was at least several times less than the amplitude of the neutron line from the 5.16 Mev level. Therefore, the 5.18 Mev state is very weakly fed by $Be^9(d,n)B^{10}$ at low energies.

III. Discussion of the Angular Distribution Data

Butler stripping curves were fitted to the observed angular distributions, using the tables of Lubitz (Lu 57). For the bound case, defined by $Q > -2.226$ Mev, Lubitz writes the angular dependence of the cross section as

$$\sigma_l(\theta) \sim \left[\frac{G_l(y) j_l(x) + j_{l-1}(x)}{(x^2 + y^2) \left[1 + \frac{(m+1)(x^2 + y^2)}{2m r_0^2 (\beta^2 - \alpha^2)} \right]} \right]^2$$

where $x = qr_0$ and $y = \kappa r_0$, and G is expressed in terms of Hankel functions by

$$G_\ell(y) = -iy \frac{h_{\ell-1}^{(1)}(iy)}{h_\ell^{(1)}(iy)}$$

In the zero-range approximation for the deuteron, $\beta = \infty$ and the denominator becomes $x^2 + y^2$. Lubitz approximates the non-zero range case by assuming $\beta = 7\alpha$ (β and α are constants in the Hulthen wave function), from which he obtains, using $r_0 = 5$ fermis, and $m/m + 1 = 1$, the expression $(x^2 + y^2)(1 + .008(x^2 + y^2))$ for the denominator in the expression for $\sigma_\ell(\theta)$. In these tables, therefore, the cross section, which depends on the 5 variables E_d , Q , m , r_0 (the nuclear radius), and θ , is expressed in terms of only two dimensionless variables, x and y .

The experimentally determined quantities, E_d , Q , and m (where m is the mass of the initial nucleus in amu) are used to evaluate the quantities

$$t = \sqrt{\frac{m+2}{2(m+1)}} \left[\frac{m}{m+2} + \frac{Q}{E_d} \right]$$

$$k_d^2 = .09567 \times 10^{26} \left(\frac{m}{m+2} \right)^2 E_d$$

$$q^2 = 2tk_d^2 \left[\frac{t^2 + 1}{2t} - \cos\theta \right]$$

$$\kappa = .2197 \times 10^{13} \sqrt{\frac{m}{m+1} |Q + 2.226|}$$

For ℓ values greater than 0, r_0 can be uniquely determined, as shown by Lubitz, by making the theoretical peak coincide with the experimental peak; otherwise, r_0 is considered to be a somewhat adjustable parameter.

For the 5.16 Mev group, the values $Q = -0.80$ Mev, $E_d = 1.91$ Mev, and $m = 9.015$ were used to evaluate $t = 0.468$,

$k_d^2 = 1.222 \times 10^{25}$, $\kappa = 2.489 \times 10^{12}$, and $q^2 = 1.144(1.3023 - \cos\theta) \times 10^{25}$. The experimental angular distribution of neutrons from the 5.16 peaks at approximately $\theta = \theta_p = 18^\circ$ in the center of mass system, from which $q(\theta_p) = 1.937 \times 10^{12}$. Therefore, $\kappa/q(\theta_p) = 1.2851 = y/x_p$. The graph in Lubitz of y/x_p versus y , for ℓ values > 0 , provides values of y and thus values for r_0 from $r_0 = y/\kappa$. The following values were obtained.

	<u>$\ell = 1$</u>	<u>$\ell = 2$</u>	<u>$\ell = 3$</u>	<u>$\ell = 4$</u>
y	1.1	3.02	4.55	6.0
r_0 (fermis)	4.42	12.13	18.28	24.1
x_p	.856	2.35	3.59	4.67

$r_0 = 4.42$ fermis, for $\ell = 1$, is the only physically reasonable value of r_0 , and therefore the correct ℓ value (unless $\ell = 0$ gives a good fit) is most likely to be $\ell = 1$. For each ℓ value we can now read from the tables σ as a function of x , for the appropriate value of y , and determine θ from $x^2 = q^2 r_0^2$. Thus, for $\ell = 1$, $y = 1.1$, and $r_0 = 4.42$ fermis, $\cos\theta = (2.91 - x^2)/2.235$. Therefore, σ can be read for increasing values of x , starting with $x = 0.8$ ($\theta \sim 0$), until the desired range of θ values has been covered.

Values used in determining the stripping curves are given below.

	<u>5.16</u>	<u>5.11</u>	<u>4.77</u>	<u>4.77</u>
E_d	1.91 Mev	1.91 Mev	1.91 Mev	1.50 Mev
Q	-0.80 Mev	-0.743 Mev	-0.408 Mev	-0.408 Mev
m	9.015 amu	9.015 amu	0.015 amu	9.015 amu
t	0.468	0.4859	0.5758	0.5482
h_d^2	$1.224(10^{25})$	$1.224(10^{25})$	$1.224(10^{25})$	$0.9612(10^{25})$
κ	$2.489(10^{12})$	$2.521(10^{12})$	$2.8106(10^{12})$	$2.8106(10^{12})$
q^2	$1.144(10^{25})$ [1.3023 - $\cos\theta$]	$1.1895(10^{25})$ [1.2720 - $\cos\theta$]	$1.4095(10^{25})$ [1.15625 - $\cos\theta$]	$1.0539(10^{25})$ [1.1862 - $\cos\theta$]
$q(\theta_p)$	$1.937(10^{12})$		$3.7215(10^{12})$	$3.1263(10^{12})$

The resulting stripping curves for the 5.16, 5.11, and 4.77 Mev levels are shown in Figures 3-13 and 3-14. For the 5.16 Mev level, $\ell_p = 1$ gives the only good fit for reasonable r_0 values. For $\ell_p = 0$, a larger value of r_0 than the rather small 4.0 fermis chosen for the curve shown would give an even worse fit to the experimental curve. Because angular distributions of neutrons to the 5.16 Mev level were not measured at back angles, it is possible that the distribution of neutrons to this level could be symmetric about 90° , implying compound nucleus formation rather than a stripping mechanism. However, if the process is stripping, $\ell_p = 1$ capture predominates. Therefore, since Be^9 has $J = 3/2^-$, the 5.16 Mev state has positive parity, and one of the J values 0, 1, 2, or 3.

A crude Coulomb correction for the captured proton has been applied to the $\ell_p = 1$ curve for the angular distribution of neutrons from the 5.16 Mev state. The corrections, as defined by Butler (Bu 57), consist

of evaluating $\kappa^{*2} = \kappa^2 + \frac{2m_c^*}{h^2} \frac{Ze^2}{r_0}$ where κ is defined

as in the tables of Lubitz, and $m_c^* = \frac{m_p m_{\text{Be}}}{m_p + m_{\text{Be}}}$. For the

$\text{Be}^9(d,n)\text{B}^{10}$ reaction, $\kappa^{*2} = \kappa^2 + \frac{(.2496)10^{26}}{r_0}$. For a

given r_0 , κ^* can therefore be obtained, and for $\ell_p \neq 0$ the tables of Lubitz can be used to obtain a new value for r_0 from $\kappa^*/q_p = y/x_p$, $y/\kappa^* = r_0$. Therefore, κ^* can be re-evaluated until a fixed value of r_0 is obtained (Sa 62). The Coulomb correction, as indicated by Figure 3-16, did significantly improve the $\ell_p = 1$, $r_0 = 4.42$ fermis fit; however, the fit was probably still not as good as that obtained by letting r_0 be a completely arbitrary parameter

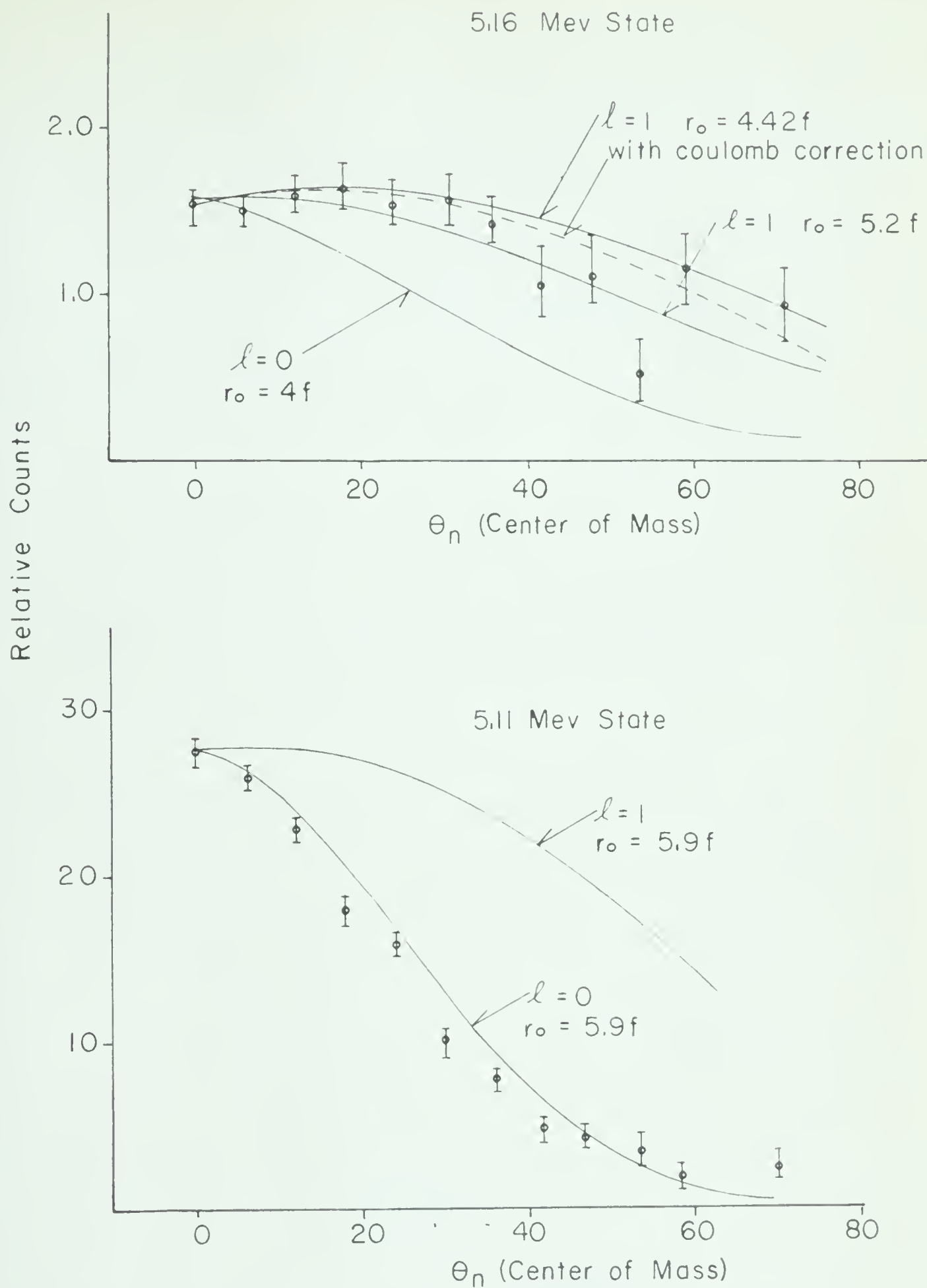


Figure 3-13 $\text{Be}^9(d,n)\text{B}^{10}$. Angular distributions of neutrons leading to the 5.11 and 5.16 Mev levels of B^{10} . The curves are Butler stripping curves.

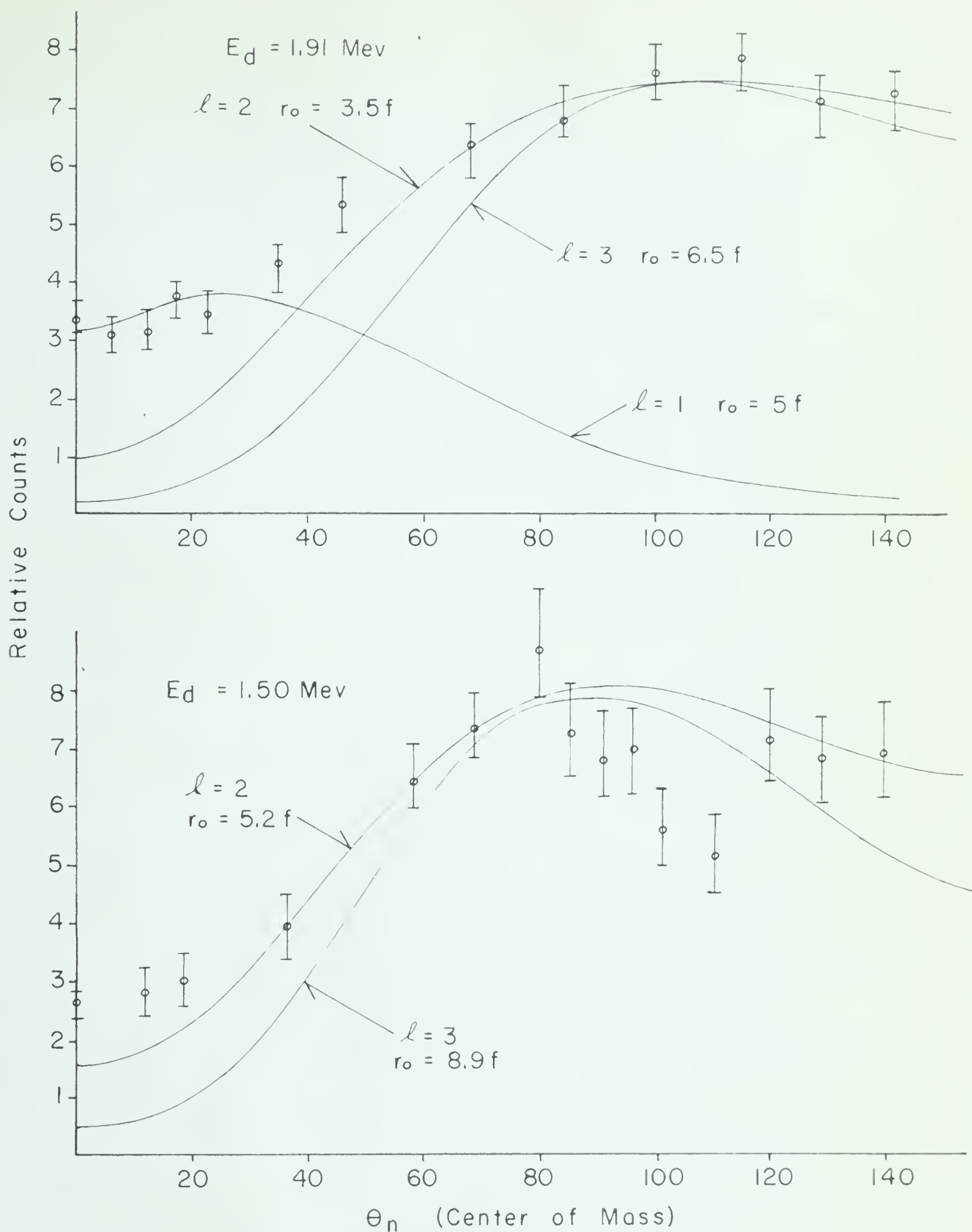


Figure 3-14 $\text{Be}^9(d,n)\text{B}^{10}$. Angular distributions for neutrons leading to the 4.77 Mev level of B^{10} . The curves are Butler stripping curves.

and choosing that value of r_0 which gives the "best" fit to the experimental data. For the 5.16 Mev state, the "best" value for r_0 so obtained was 5.2 fermis.

At angles up to 70° in the center of mass system the experimental angular distribution data for the 5.11 Mev level of B^{10} are very well fitted by an $l_p = 0$, $r_0 = 5.9$ fermis Butler stripping curve. Since the angular distribution data for the unresolved 5.11, 5.16 doublet does not peak significantly at back angles (at least for angles up to 150°), then the $l_p = 0$ fit for the 5.11 Mev level is almost certainly good up to 150° in the center of mass system. The 5.11 Mev state of B^{10} should have negative parity, and J values of 1 or 2.

The Butler stripping fits to the 4.77 Mev level are not as good as those to the 5.11 and 5.16 Mev levels, and partly because of this, the angular distribution measurements were made at two different energies. If the 4.77 Mev level has positive parity and J values of 0, 1, 2, or 3 (Wi 53, Bo 54, Wa 57, Me 59, Ta 61), p-wave proton capture should predominate. At both 1.9 Mev and 1.5 Mev the experimental data are reasonably well-fitted by either $l_p = 2$ or $l_p = 3$ stripping curves; the $l_p = 1$ curve definitely does not fit the data. $l_p = 2$ stripping would require the parity of the 4.77 Mev level to be negative, in disagreement with previously reported measurements on this state. It is possible that the angular distribution would change at a higher bombarding energy, as observed for the 3.58 Mev level of B^{10} (Sa 58, Ne 60), or that the angular distribution to this level cannot be fitted by simple stripping theory.

IV. Partial Width Measurements

(a) Identification of Gamma-Decay from the 5.16 Mev State

It is energetically possible for the 5.16, 5.11, and 4.77 Mev levels of B^{10} to decay by either alpha or gamma emission. If $T = 0$, alpha-decay can be expected to predominate; if $T = 1$, alpha-decay should be inhibited, and gamma-decay may compete successfully with alpha-decay. It was therefore of interest to measure the partial widths of the 5.16, 5.11, and 4.77 Mev states.

Neilson et al (Ne 60) have reported observing neutrons from the 5.16 Mev level in coincidence with gamma-rays, but have not observed neutrons from the 5.11 Mev level by the coincidence method. As a further check on these observations, the following experiment was performed. Beryllium and B^{10} targets of approximately equal thickness were mounted opposite each other in the target holder. Using a 1.91 Mev pulsed deuteron beam, the 5.11, 5.16 doublet spectrum was first recorded at a counter angle of 30° . The neutron flight path was 3 meters. A 50 nsec delay was then inserted between the neutron counter and the time sorter, and the target rotated 180° to expose the boron to the beam. Neutron spectra from the 6.50 Mev level were then recorded at counter angles of 30° and 45° . The 5.11, 5.16 doublet spectrum was observed to fall between the two 6.50 Mev spectra (see Figure 3-15). The beam flipper was then switched off, the NE 102 gamma detector mounted close to the target, and gamma-coincidence time-of-flight spectra were recorded using identical conditions of beam energy, counter distance, and angles. The same 50 nsec delay was used in the coincidence run as had been used in the beam flipper runs. The $Be^9(d,n)B^{10}$ peak, in the gamma-coincidence run, was observed to fall well to the left of

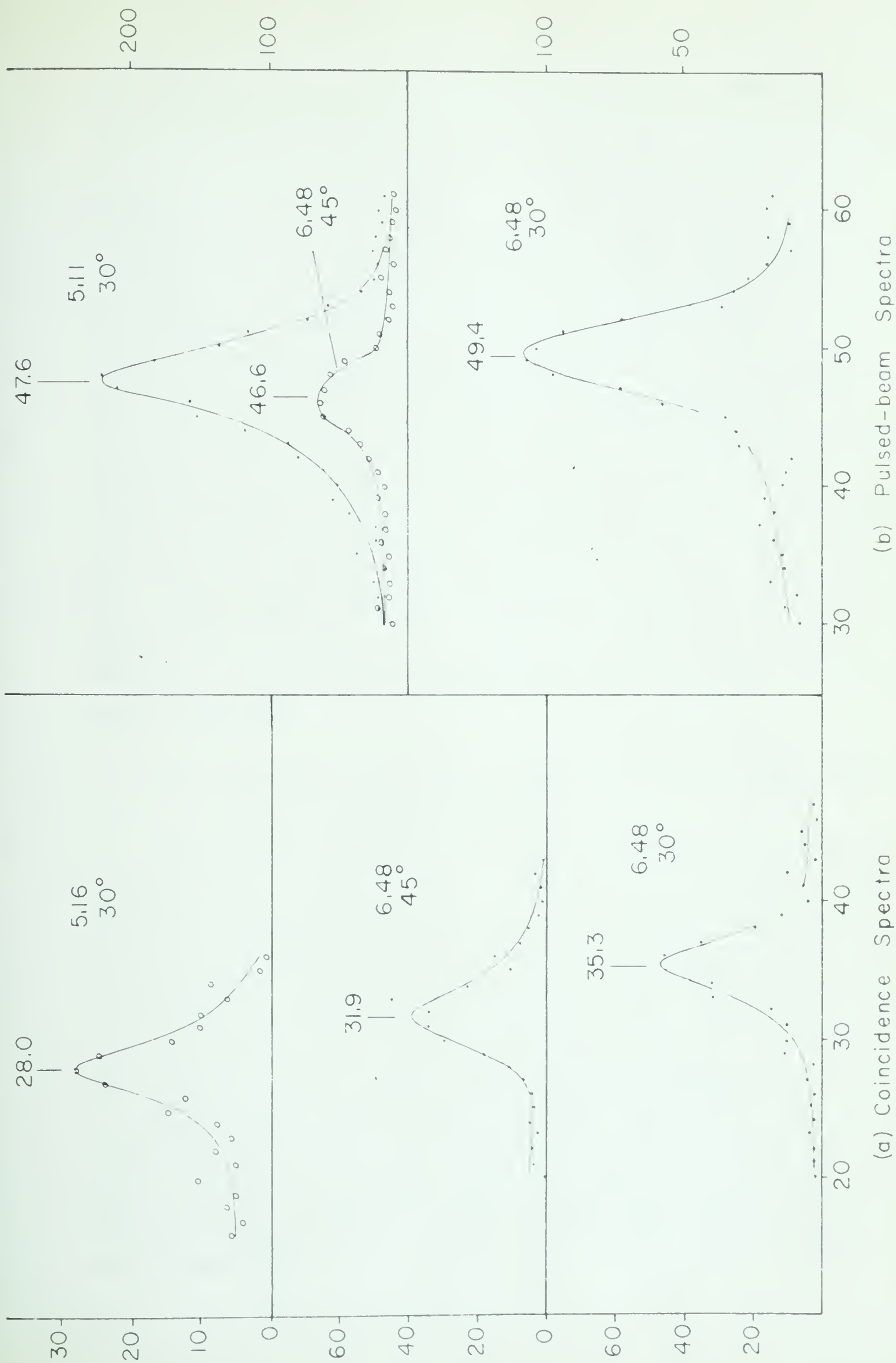


Figure 3-15 $Be^9(d,n)Be^{10}$. Comparison of pulsed beam and coincidence spectra, showing that the 5.11 Mev level in Be^{10} decays almost entirely by alpha-emission.

the spectra from the 6.50 Mev level, corresponding to an increased delay, and therefore to a lower neutron energy.

Calculated delays for the neutron groups seen in this experiment are as follows:

5.16 group, $t = 221.6$ nsec (neutron flight time only)

5.11 group, $t = 215.3$ nsec (neutron flight time only)

6.48 group, $\theta = 45^\circ$, $t = 165.9 + 50 = 215.9$ nsec

6.48 group, $\theta = 30^\circ$, $t = 162.5 + 50 = 212.5$ nsec

Since the time scale is approximately 1 nsec per channel, the relative position on the pulse-height analyser of the neutron group from $\text{Be}^9(d,n)\text{B}^{10}$ agrees well with the expected position for neutrons from the 5.11 Mev state for the pulsed beam run, and with the expected position of neutrons from the 5.16 Mev state for the gamma-neutron coincidence run. It is therefore certain that the 5.11 Mev state of B^{10} decays almost entirely by alpha emission; that is, for this level $\Gamma_\alpha \sim \Gamma$, $\Gamma_\gamma \ll \Gamma$. The following section will show that the 5.16 Mev state decays almost entirely by gamma emission.

(b) Partial Width Measurement for the 5.16 Mev Level

(i) Experimental method

The following method was used to measure the ratio of Γ_γ/Γ for the 5.16 Mev level. Spectra were recorded of the resolved neutron groups from the 5.11 and 5.16 Mev states. For these measurements the flight path was 5.1 meters, and the neutron counter was at an angle of 30° with respect to the incident 1.91 Mev pulsed deuteron beam. A comparison spectrum was then recorded of the neutron group leading to the 6.48 Mev state in C^{11} under identical conditions. The beam pulsing system was then switched off, the flight path shortened to 1 meter, and coincident neutron-gamma spectra were recorded of neutrons leading to the 5.16 Mev level of B^{10} , and to the 6.48 Mev level of C^{11} under several gamma bias conditions.

If the absolute efficiency of the gamma-ray detector and the gamma branching ratios of the 5.16 Mev state are known, the expected contribution from gamma-ray events to the total intensity as seen by pulsed beam measurements can be calculated directly. The ratio of the gamma-decay contribution to the total intensity should equal the ratio of the gamma width to the total width. Neutron spectra from the 6.48 Mev state in C^{11} can be used to provide a measurement of the absolute gamma-ray efficiency of the NE 102 detector. The 6.48 Mev state can decay only by gamma emission; that is, for this state, $\Gamma_{\gamma} = \Gamma$. Consequently, the ratio of the normalized neutron yield observed during neutron gamma coincidence measurements to the yield during pulsed beam measurements should equal the NE 102 gamma-ray efficiency for the gamma-ray energies emitted during the decay of the 6.48 Mev state. However, the relative efficiencies for the two sets of cascade gamma-rays emitted during the decays of the 5.16 Mev state in B^{10} and the 6.48 Mev state in C^{11} and the gamma-ray branching ratios for both these levels must both be known. If an independent measurement of the absolute gamma-ray efficiency of the NE 102 counter is used, the neutron spectra for the 6.48 Mev level and the branching ratio of the 6.48 Mev state are unnecessary. However, no matter how the gamma-ray efficiency for the NE 102 counter is defined, there must exist no strong anisotropic gamma correlations with respect to the fixed neutron direction. Neilson et al (Ne 60) have shown that this assumption is well justified.

An estimate was made of the absorption of 1 Mev neutrons in traversing 5 meters of air, using neutron total cross sections taken from Supplement no. 1 to BNL 325 (Hu 60). Values of $\sigma = 2$ barns/atom for nitrogen, and $\sigma = 8$ barns/atom for oxygen were used. The total absorption, given by $e^{-\sigma N}$, is approximately 5% for the 5 meter flight

path; since this is well within experimental error, the results were not corrected for this absorption.

(ii) γ -Decay schemes for the 5.16 and 6.48 Mev levels

The gamma-decay scheme for the 5.16 Mev state in B^{10} was taken from Sprenkel and Daughtry (Sp 61a), and is reproduced in Figure 3-16. The possible gamma-ray energies, together with their probabilities of emission during the gamma-decay of one nucleus from the 5.16 Mev state, are as follows:

5.16 Mev	0.07
4.44	0.29
3.01	0.64
2.15	0.10
1.43	0.18
1.02	0.35
0.72	0.82
0.41	0.35

The total summed probability is 2.8; that is, on the average, 2.8 gamma-rays are emitted during each gamma-decay of a nucleus from the 5.16 Mev state. It was observed, during the coincidence time-of-flight experiments, that the counting rate for neutrons from the 6.48 Mev state in C^{11} decreased linearly with increasing gamma side-channel bias, indicating that the gamma-decay was proceeding almost entirely by emission of a single gamma-ray.

The change in counting rate for gamma-coincident neutrons from the 6.48 Mev state as a function of gamma-ray bias energy was compared with the change in counting rate for 6.14 Mev gamma-rays obtained from the 340 kev resonance in $F^{19}(p,\alpha,\gamma)O^{16}$. The two curves, shown in Figure 3-17, very nearly coincide, indicating that the 6.48 Mev state decays almost entirely by 6.48 Mev gamma-rays. For comparison, the change in counting rate of

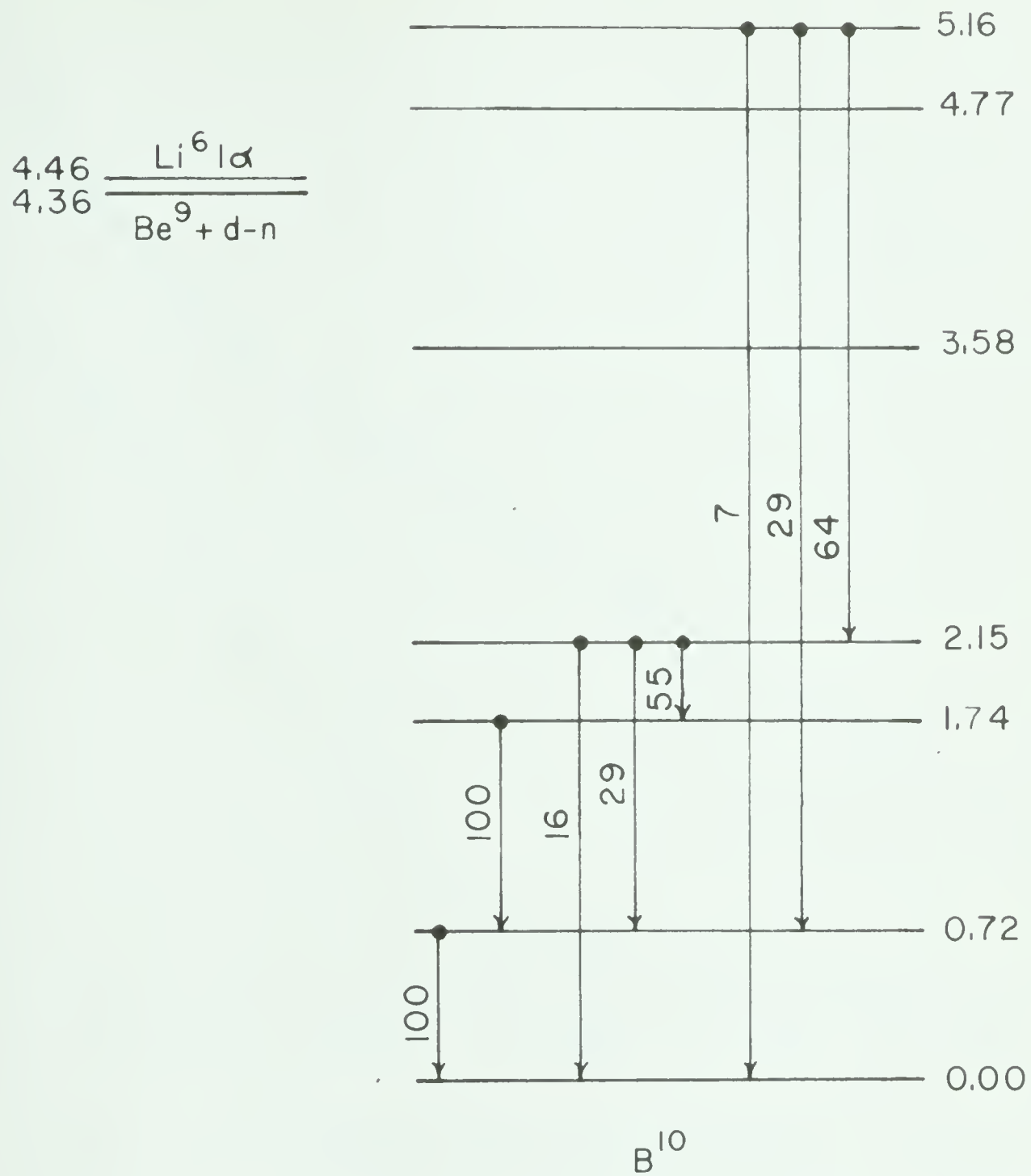


Figure 3-16 Gamma-decay of the 5.16 Mev level in B^{10} . Taken from Sprenkel and Daughtry (Sp 61a).

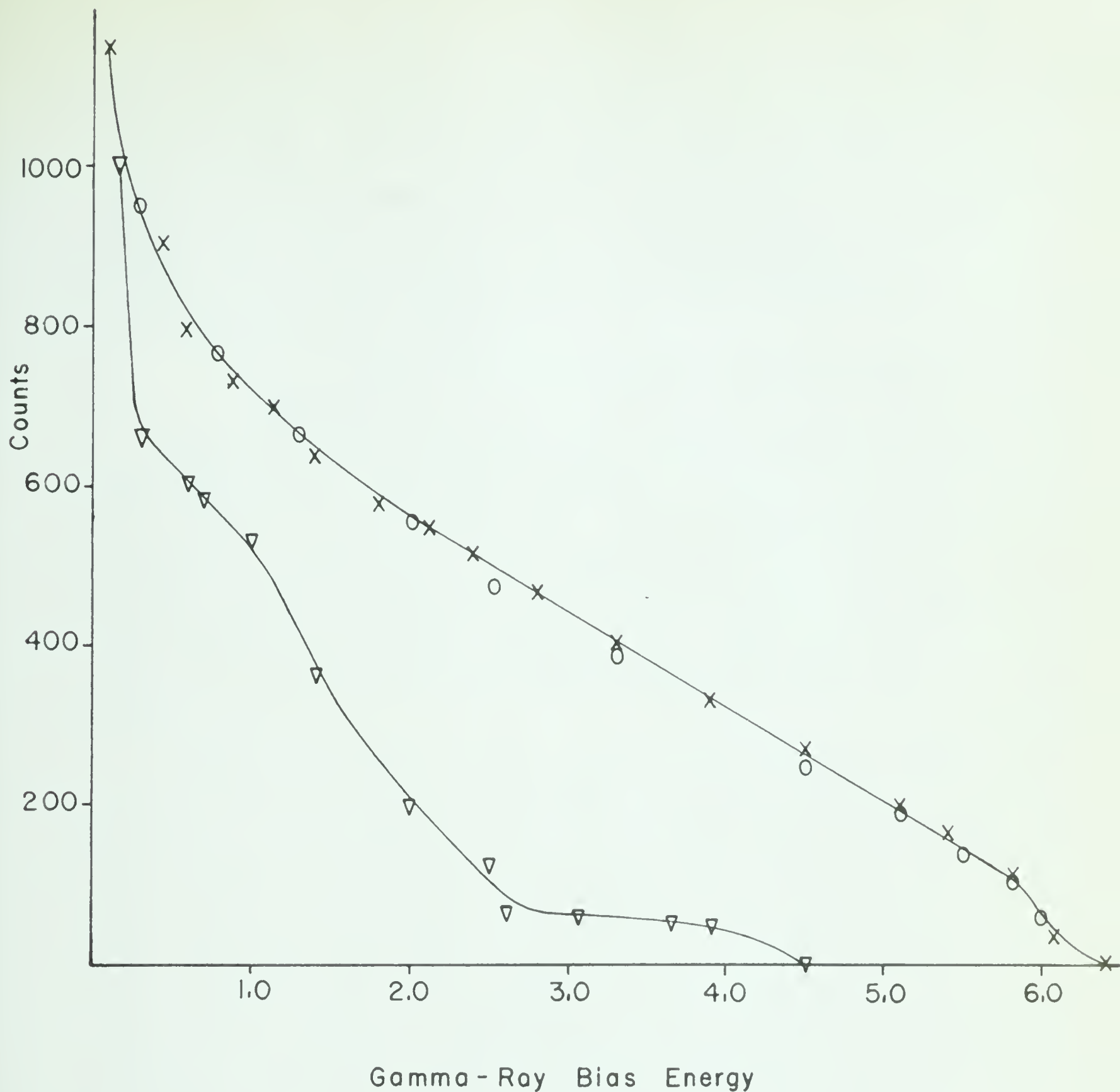


Figure 3-17 Variation in counting rate with gamma bias.
 x - 1.14 Mev gamma-rays from $F^{19}(p,\alpha\gamma)O^{16}$
 o - gamma-coincident neutrons from the 6.48 Mev state in C^{11}
 Δ - gamma-coincident neutrons from the 5.16 Mev level of B^{10}

gamma-coincident neutrons from the 5.16 Mev state of B^{10} is also shown. For the purposes of this experiment, the 6.48 Mev state in C^{11} was assumed to decay 90% of the time by 6.48 Mev ground state transitions, and to cascade through the 4.26 Mev level with a 10% probability. Chapter IV of this thesis shows that this assumption is reasonably well justified.

(iii) Gamma-ray efficiencies for the NE 102 counter

The gamma-ray efficiency for the NE 102 counter has been measured at gamma-ray energies of 1.28, 2.62, and 6.14 Mev as a function of bias. These measurements are discussed in Appendix I. The approximate efficiencies for the gamma-ray energies seen in this experiment have been determined through interpolation. The resulting curves of efficiency versus bias energy are shown in Figure 3-18.

Gamma-coincident neutron spectra from the 5.16 Mev level of B^{10} and from the 6.48 Mev level of C^{11} were recorded using gamma-ray biases of 0.28, 0.58, 0.82, 1.42, and 2.62 Mev, different biases being used in order to check on the experimental consistency. For each bias used the gamma-ray efficiencies for the gamma-decay of the 5.16 Mev state were obtained by multiplying the appropriate gamma-ray efficiency by the relative probability of emission of that gamma-ray during the decay process. The total gamma-ray efficiency for gamma-rays from the 5.16 Mev state is the sum of the efficiencies for the separate gamma-ray energies. Gamma-ray efficiencies for the decay of the 6.48 Mev state were similarly obtained, using 0.9, 0.1, and 0.1 as the relative probabilities of emission of 6.48, 4.26, and 2.22 Mev gamma-rays during each decay. The efficiency values obtained for each bias are listed below.

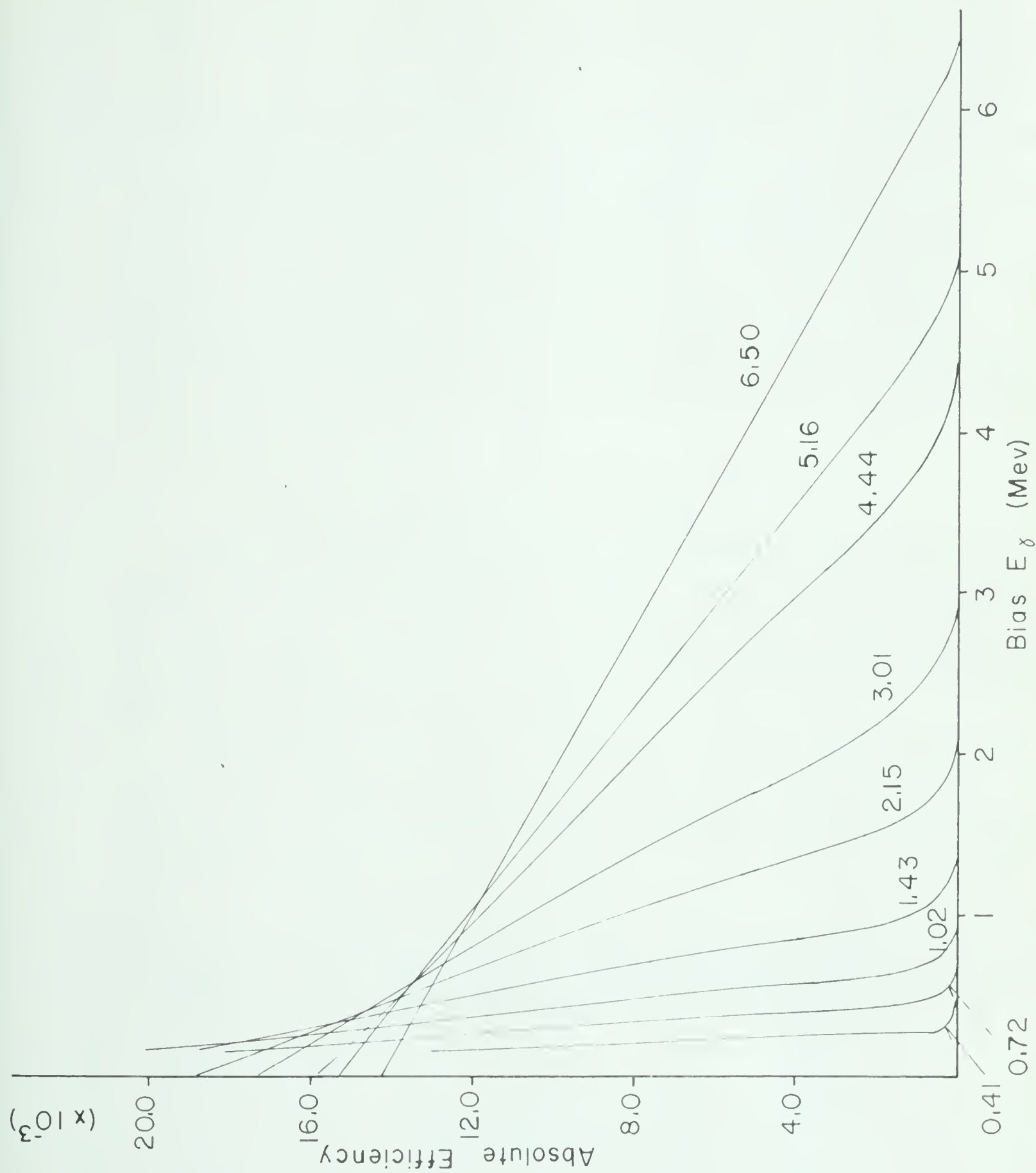


Figure 3-18 Derived gamma-ray efficiencies for the NE 102 counter, plotted as a function of gamma-ray bias.

Bias, Mev	5.16 γ -ray efficiency	6.48 γ -ray efficiency
0.28	35.1(10^{-3})	15.3(10^{-3})
0.58	18.2(10^{-3})	14.3(10^{-3})
0.82	14.3(10^{-3})	13.5(10^{-3})
1.42	9.00(10^{-3})	11.4(10^{-3})
2.62	2.40(10^{-3})	8.16(10^{-3})

An experimental difficulty was caused by the non-linearity of the bias setting versus gamma-ray energy curve (see Appendix II), which made it difficult to determine the bias energy accurately, especially for high bias settings. To reduce error from this source, bias energies greater than 2.62 Mev, the gamma-ray energy available from a RdTh source, were not used.

(iv) Experimental results

The pulsed beam measurements, taken at 30° and 5.1 meters, with an integrated target current of 50 μ coulombs for each run, yielded 143 ± 15 counts for neutrons from the 5.16 Mev state of B^{10} , and 1990 ± 100 counts for neutrons from the 6.48 Mev state of C^{11} .

The gamma-coincidence neutron spectra were recorded at 30° and 1 meter. The data, corrected for gamma-ray efficiency, and normalized to 5.1 meters and 50 μ coulombs, are given below.

Bias Energy (Mev)	"Normalized" counts to the 6.48 Mev level	"Normalized" counts to the 5.16 Mev level
0.28	2370 ± 100	135 ± 20
0.58	2160 ± 100	193 ± 30
0.82	2440 ± 100	208 ± 30
1.42	2420 ± 100	140 ± 20
2.62	2540 ± 100	150 ± 20

The original data are tabulated in Appendix II. The data for the decay of the 6.48 Mev state are in agreement except for the measurement at a bias of 0.58 Mev. The data for the decay of the 5.16 Mev state are not, as expected, in such good agreement, partly because of the low yield to this state, and partly because of the complexity of the gamma-decay of this state, which makes the accurate estimation of gamma-ray efficiency difficult.

The unweighted average for the normalized 5.16 counts from the coincidence spectra is 166 ± 20 , compared with 142 ± 15 from pulsed beam measurements. Therefore, the value obtained for Γ_γ/Γ for the 5.16 Mev state is 1.17 ± 0.2 .

The unweighted average for the 6.48 counts from the coincidence spectra is 2400 ± 100 , compared with 1990 ± 150 counts when using a pulsed beam. Therefore, the gamma efficiency values are apparently too low by 20%; if we apply this efficiency correction to the counts from the 5.16 Mev state, we obtain the value of 138 ± 20 counts for the unweighted average during the coincidence runs. Therefore, the value obtained for Γ_γ/Γ for the 5.16 Mev state becomes 0.97 ± 0.2 .

It is reasonably certain that $\Gamma_\gamma/\Gamma \geq 0.8$; that is, within the experimental limits, the 5.16 Mev state decays entirely by gamma emission. The apparent error in the measured gamma-ray efficiencies of 20% is difficult to explain; an error of 10% would be reasonable. A possible explanation could be that the pulsed beam does not hit exactly the same portion of the target as does the d.c. beam. However, when using the beryllium target, a BF_3 monitor counter showed that the neutron count rate from the target (per $\mu\text{coulomb}$ of integrated target current) when the beam was pulsed was identical to the count rate when a d.c. beam was used. Possibly, also, the gamma correlation with respect to the fixed neutron direction is not quite isotropic.

(c) Decay of the 4.77 Mev Level in B^{10}

A search was made for gamma-coincident neutrons from the 4.77 Mev state in B^{10} . Successive $Be^9(d,n)^{10}$ pulsed beam and gamma-coincidence neutron spectra were recorded, and are shown in Figure 3-19. The time scales for the two runs are almost identical. The flight path was 1 meter, the counter angle was 30° , and the deuteron energy was 1.6 Mev. At this low energy, the line from the 5.16 Mev state is not sufficiently intense to appear in the coincidence spectrum. A higher deuteron energy was desirable to obtain a greater yield to the 4.77 Mev level, but was not available at the time. However, under the experimental conditions, no gamma-coincident neutrons from the 4.77 Mev state were observed. From the measurements, the probability of gamma-decay of the 4.77 Mev level is at least a factor of 10 less than the probability of alpha-decay.

V. Discussion

To summarize the neutron time-of-flight work on the 5.16, 5.11, and 4.77 Mev states of B^{10} , the 5.16 Mev state decays almost entirely by gamma emission, and therefore should have $T = 1$, while the 5.11 and 4.77 Mev states decay almost entirely by alpha emission, and should be $T = 0$ states. At a deuteron energy of 1.9 Mev, the stripping angular distribution for the 5.16 Mev state is well fitted by $\ell_p = 1$ capture at angles up to 70° in the center of mass system, which was the maximum angle at which neutrons to this level were resolved from the neutron group to the 5.11 Mev state. The results are therefore consistent with the assignment $J^\pi = 2^+$ for the 5.16 Mev state. The stripping angular distribution for the 5.11 Mev state is well fitted by $\ell_p = 0$ capture, and is therefore consistent with the assignment $J^\pi = 2^-$ for

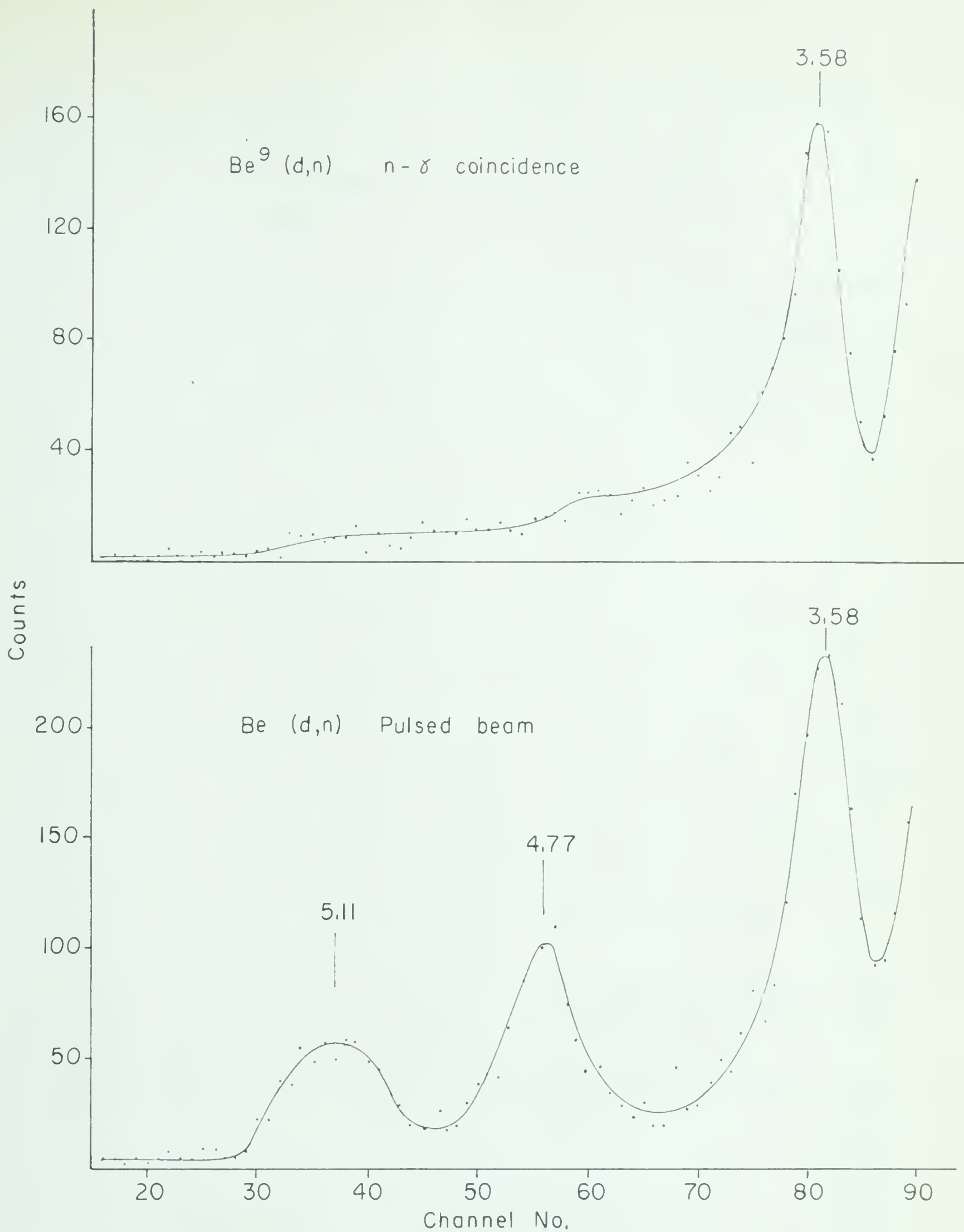


Figure 3-19 $\text{Be}^9(d,n)\text{B}^{10}$. A search for gamma-coincident neutrons from the 4.77 Mev level of B^{10} .

this state. The ratio of the intensity of the neutron group from the 5.11 Mev level to that of the group from the 5.16 Mev level at 1.9 Mev deuteron energy decreases from $15.5 \pm 3 : 1$ at 0° to approximately $2 : 1$ at 70° in the center of mass system.

At deuteron energies of 1.91 and 1.50 Mev, the stripping angular distribution to the 4.77 Mev state could either be fitted by $\ell_p = 2$ or by $\ell_p = 3$ capture. The assignment of $\ell_p = 2$ capture to the 4.77 Mev state would imply negative parity for this level, a doubtful assignment in view of already published work.

Little can be said regarding the failure to observe the 5.18 Mev state in B^{10} . In the work of Sprenkel, Olness, and Segel, this state was fed by $Li^6 + \alpha$, and detected through observation of gamma-decays of the state. The gamma-ray detection efficiency is larger than the detection efficiency for neutrons in the present time-of-flight work; therefore, it is not surprising that the 5.18 Mev level was not observed here. Furthermore, it is possible that the 5.18 Mev state is more easily formed when fed by $Li^6 + \alpha$ than when fed by $Be^9(d,n)B^{10}$. The failure to observe the 5.18 Mev state in the present work does tend to support the suggestion by Warburton and Chase (Wa 62) that the 5.18 Mev state may well belong to a doubly excited configuration and, therefore, should not be seen by single nucleon direct interactions.

The present work, therefore, is in complete agreement with the work of Warburton and Chase; the 5.16 Mev state observed in $Be^9(d,n)B^{10}$ work is almost certainly the $J^\pi = 2^+$, $T = 1$ isotopic spin analog of the first excited states of Be^{10} and C^{10} .

CHAPTER IV. THE 6.48 Mev STATE IN C^{11}

I. Introduction

There has been little published work concerning the decay of the 6.48 Mev level in C^{11} . McDonnell et al (Mc 60a), through measurements of n- γ coincidences in the reaction $B^{10}(d,n,\gamma)C^{11}$, reported that the dominant cascade from the 6.48 Mev state is through the 4.26 Mev state, and that the intensity of this cascade is somewhat less than that of the direct ground state transition. James (Ja 61a), in a study of gamma-rays from the 1.14 Mev resonance in $B^{10}(p,\gamma)C^{11}$, reported that two-thirds of the transitions from the 6.48 Mev level were directly to the ground state; the remaining one-third cascaded through the 4.26 Mev state to the ground state. Bent et al (Be 55), using a magnetic lens pair spectrometer to study the radiations produced by 2 Mev deuterons on B^{10} , observed intense ground state transitions from the 6.48 Mev state in C^{11} , but saw no other gamma-ray transitions attributable to the decay of excited states of C^{11} . In a similar experiment Sample et al (Sa 55), using a 3 crystal pair spectrometer, observed ground state transitions from the 4.75 and 6.48 Mev states of C^{11} and also transitions from the 7.40 to the 1.99 Mev levels.

The branching ratio in the decay of the 6.48 Mev state in C^{11} should be approximately the same as the branching ratio for the decay of the mirror analog of this state in B^{11} . The spins and parities of states in B^{11} have been established up to an excitation of 6.76 Mev (Bi 60, Do 61, Hi 61, Gr 62). The states in C^{11} have been identified on the basis of mirror nucleus correspondence, from which it

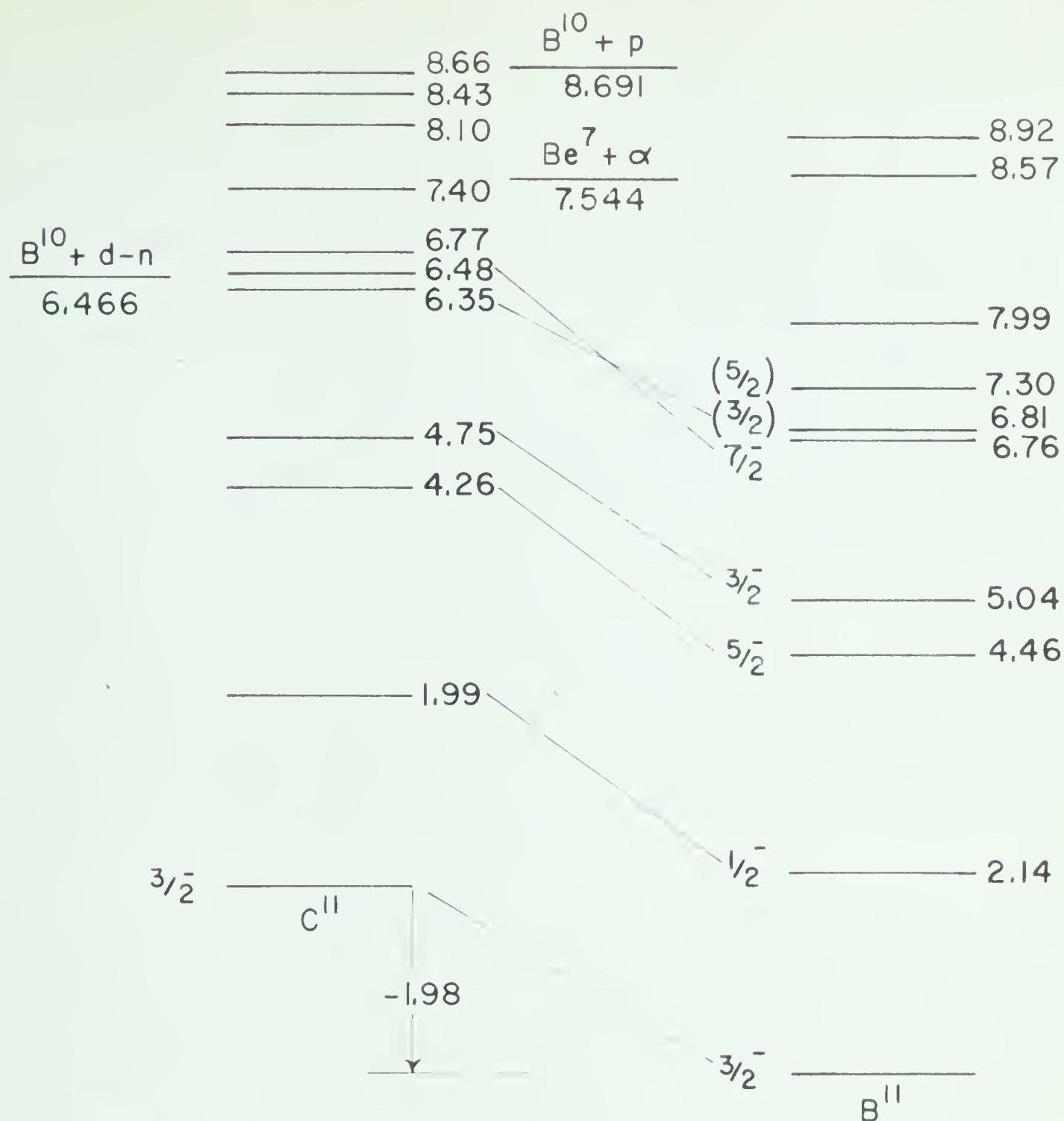


Figure 4-1 Mirror nucleus comparison of C^{11} and B^{11} . Q-values for $(B^{10} + d - n)$, $(B^{10} + p)$, and $(Be^7 + \alpha)$ refer to the ground state of C^{11} .

has been found that the 6.76 Mev state in B^{11} , with $J = 7/2^-$, is the mirror analog of the 6.48 Mev state in C^{11} . The 6.76 Mev state in B^{11} and the 6.48 Mev state in C^{11} are both strongly excited by $\ell_p = 1$ transitions in their respective stripping reactions, while the 6.81 Mev state in B^{11} and the 6.35 Mev state in C^{11} are only weakly excited (Hi 61). Energy level diagrams for B^{11} and C^{11} , taken from Landolt-Bornstein (La 61) are shown in Figure 4-1.

The 6.76 Mev state in B^{11} has been found to decay either by $E(2)$ transitions directly to the ground state, or by $M(1)$ transitions to the 4.46 Mev state, which then decays directly to the ground state (Do 61). However, measurements of the branching ratio for the decay of the 6.76 Mev state are in disagreement; Ferguson et al (Fe 58) found the $E(2)$ transition to be approximately 5 times as strong as the $M(1)$, while Green et al found the ratio to be 1.75:1.

The independent particle model calculations of Kurath (Ku 57) for the ℓ_p shell, using a reasonable value for the ratio of the spin orbit to the central force, predict a vanishing $M(1)$ transition strength for a $7/2^-$ to $5/2^-$ transition in an $A = 11$ nucleus (Fe 58). A moderately strong cross over transition should then be expected.

Finally, the decay scheme of the 6.48 Mev state of C^{11} was of interest in the measurement of the partial width of the 5.16 Mev state in B^{10} . It was observed (see Figure 3-17) that the ground state transition in the decay of the 6.48 Mev state was very intense. However, it is difficult to investigate accurately the gamma-ray branching ratios with the NE 102 counter, since the pulse-height distribution spectrum from this crystal for high energy gamma-rays is nearly flat down to zero energy. (see Appendix II).

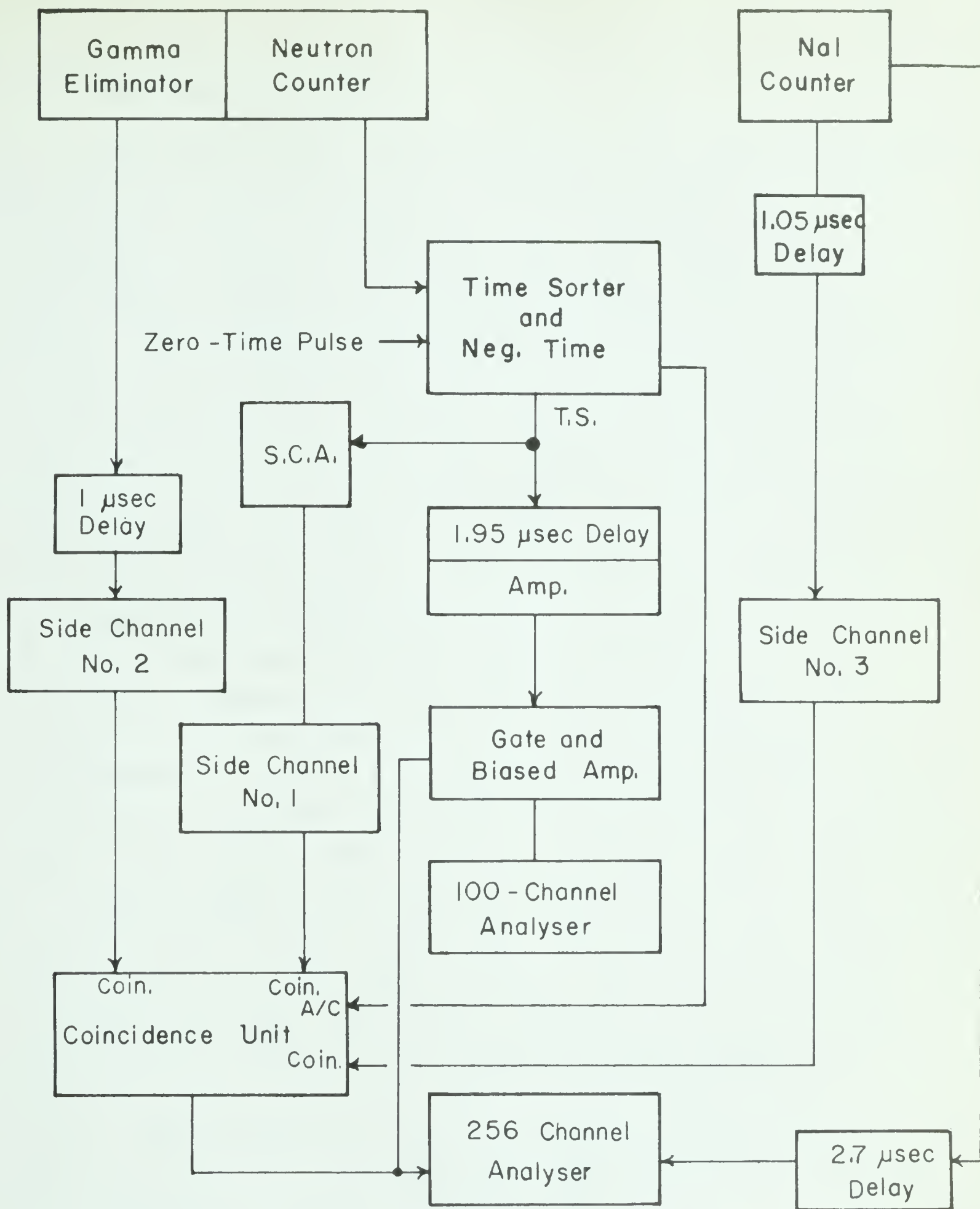


Figure 4-2 A block diagram of the experimental arrangement used in the measurement of the decay of the 6.48 Mev state of C^{11} .

II. Experimental Method

The decay of the 6.48 Mev state in C^{11} has been studied by means of the $B^{10}(d,n,\gamma)C^{11}$ reaction. Gamma-rays from the decay of the 6.48 Mev state were observed using a collimated 4 inch by 4 inch NaI crystal, the NaI counter being gated by means of neutrons leading to the 6.48 Mev state. The neutrons, observed in the liquid scintillation counter, were selected by means of pulsed-beam time-of-flight measurements. The resulting gamma-ray coincidence spectrum was displayed on a 256 channel pulse-height analyzer*. As an experimental check, the neutron coincidence time-of-flight spectrum was recorded simultaneously on a 100 channel pulse-height analyzer.** A block diagram of the experimental arrangement is given in Figure 4-2.

The experiment differed slightly from the work of McDonnell et al; in their work the NaI counter was used to provide the zero-time pulse for the time-of-flight spectrometer. In the present work the zero-time was provided by a pulsed beam; the NaI counter was not used as part of the neutron spectrometer. In fact, the operation of the spectrometer was unchanged from its operation in the $Be^9(d,n)B^{10}$ work, except that the neutron side-channel was not used with the spectrometer. Since the gamma-ray eliminator provides some energy selection, not all of the discrimination against small pulses usually provided by the side-channel was lost, and the resolution of the neutron spectrometer was not too seriously impaired. A typical $B^{10}(d,n)C^{11}$ time-of-flight spectrum obtained during the experiment is shown in Figure 4-3.

*Technical Measurements Corporation, 441 Washington Avenue, North Haven, Connecticut.

**Phillips Electronic Industries, Ltd.

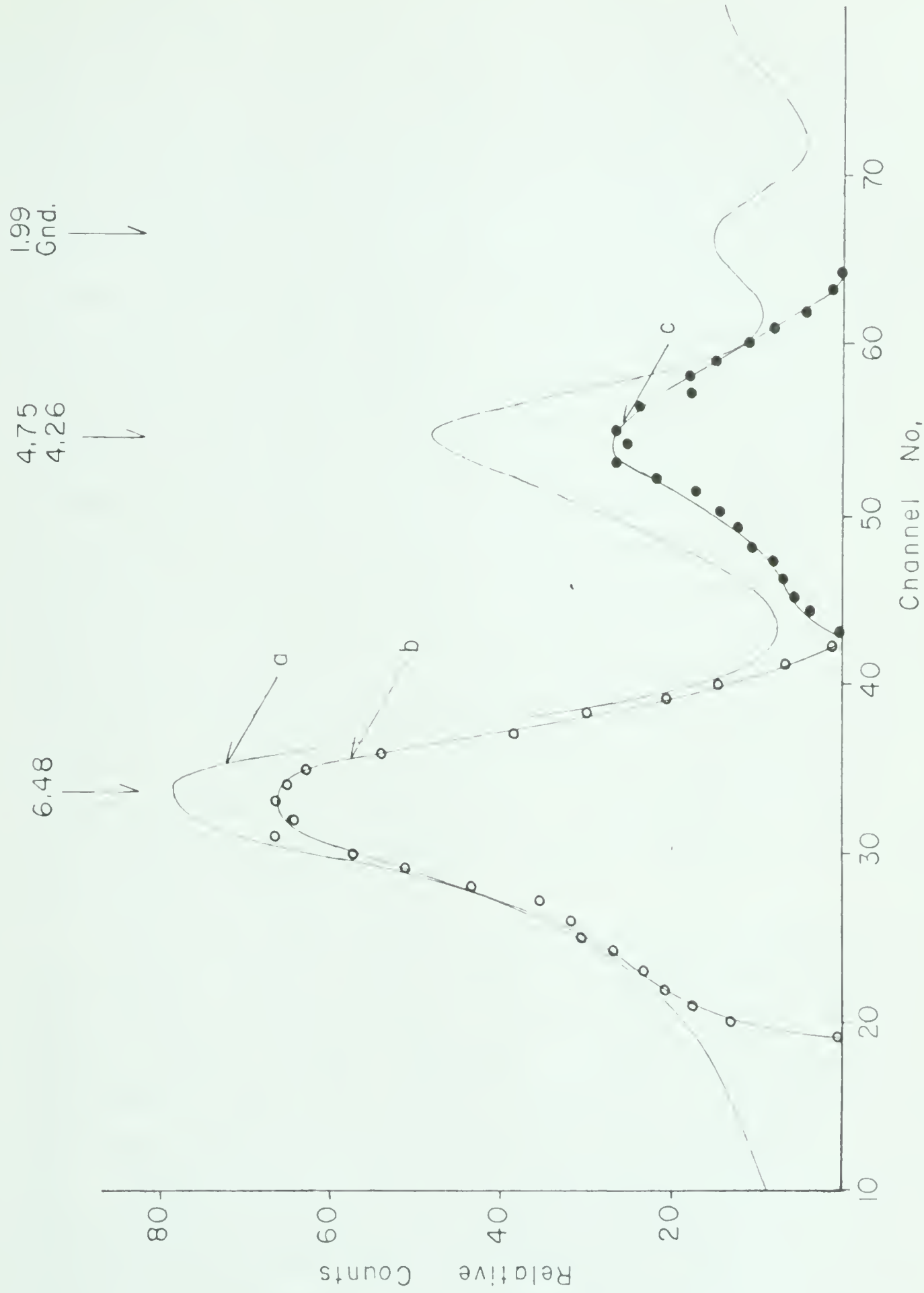


Figure 4-3 $\text{Be}^9(\text{d}, \text{n})\text{B}^{10}$. Neutron time-of-flight spectra. $E_d = 1.5 \text{ Mev}$, $S_n = 50 \text{ cm}$

(a) Ungated spectrum

(b) Single-channel analyzer gated to accept neutrons leading to the 6.48 Mev level

(c) Single-channel analyzer gated to accept neutrons leading to the 4.26 and 4.75 Mev levels

In order to ensure that the 6.48 Mev state in C^{11} had been formed, it was necessary to select from the neutron time-of-flight spectrum only neutrons leading to the 6.48 Mev state. This was done by self-gating the output of the time-sorter onto the 100 channel pulse-height analyzer. A single-channel analyzer*, whose window was set to accept only pulses whose amplitude corresponded to neutrons to the 6.48 Mev level, was used to provide the required gating pulses. Since the output of the single-channel analyzer also gated the NaI counter, the self-gated time-of-flight spectrum on the 100 channel analyzer represented those neutron pulses available to trigger the NaI counter. It was therefore possible to monitor and control the amplitude of the neutron gating pulses accurately. Figure 4-4 shows, in addition to the normal neutron time-of-flight spectrum, a self-gated neutron spectrum taken with the single-channel analyzer set to accept only neutrons from the 6.48 Mev state. The spectrum also contains any contributions from neutrons leading to the 6.77 and 6.35 Mev states. These states are, however, so weakly fed, that these contributions are insignificant (see Appendix V). A spectrum is also shown with the gate set to accept neutrons leading to the 4.26 and 4.75 Mev levels of C^{11} .

The same coincidence unit was used to drive both the 100 channel and the 256 channel pulse-height analyzer. The neutron gating pulses, as described above, were obtained from a single-channel analyzer. Coincidence pulses from the gamma-eliminator circuit and anti-coincidence pulses from the negative-time-eliminator were provided in the usual way. Output pulses from the coincidence unit also demanded input pulses from the NaI counter; these pulses were brought in through the side-channel previously removed from the neutron spectrometer. The resolving time for neutron-gamma coincidences was 0.1 μ second. The electronic delays in the system were adjusted by using a square wave pulse.

*Tracerlab Inc., SC 76 M Spectrometer.

generator which provided three simultaneous outputs.*

The B^{10} target contained $220 \mu\text{gm}/\text{cm}^2$ of B^{10} with a B^{11} impurity of less than 1%.** Spectra were recorded with the neutron counter at angles of 30° , 0° , and -30° with respect to the incident 1.5 Mev deuteron beam. Angles of 30° were chosen to correspond with the peak of the angular distribution curve for neutrons from the 6.48 Mev state. Neutron flight paths of 50 cm and 40 cm were used, these being the optimum distances consistent with clear separation of neutrons leading to the 6.48 Mev level and reasonable counting rates. The NaI crystal was fixed at the largest backward angle that could be attained; this angle was -115° with respect to the incident beam. Such positioning of the NaI counter had the advantage that fewer neutrons from the (d,n) reaction were available to interact with the iodine in the crystal. The 2 inch thick lead collimator subtended a half-angle of 15° at the target. Figure 4-4 shows the locations of the NaI gamma counter and the liquid scintillator neutron counter used in the experiment.

The experimental runs were performed with total counting rates from the NaI counter of approximately 5000 and 2500 counts per second above a bias of 1 Mev. At both counting rates large photomultiplier count-rate gain shifts were observed. Since the time constant for the establishment of a fixed gain at a given counting rate is approximately 15 minutes (Mi 61), the beam was switched onto the target at the desired beam current for approximately 1/2 hour before spectra were recorded. During runs the beam current was held as nearly constant as possible. Every half-hour during runs spectra were recorded and examined

*Epic Model 300 Square Pulse Generator, Electrical and Physical Instrument Corporation, 25 West 43 St., New York 36, New York.

**Supplied by Atomic Energy Research Establishment, Harwell, Didcot, Berkshire, England.

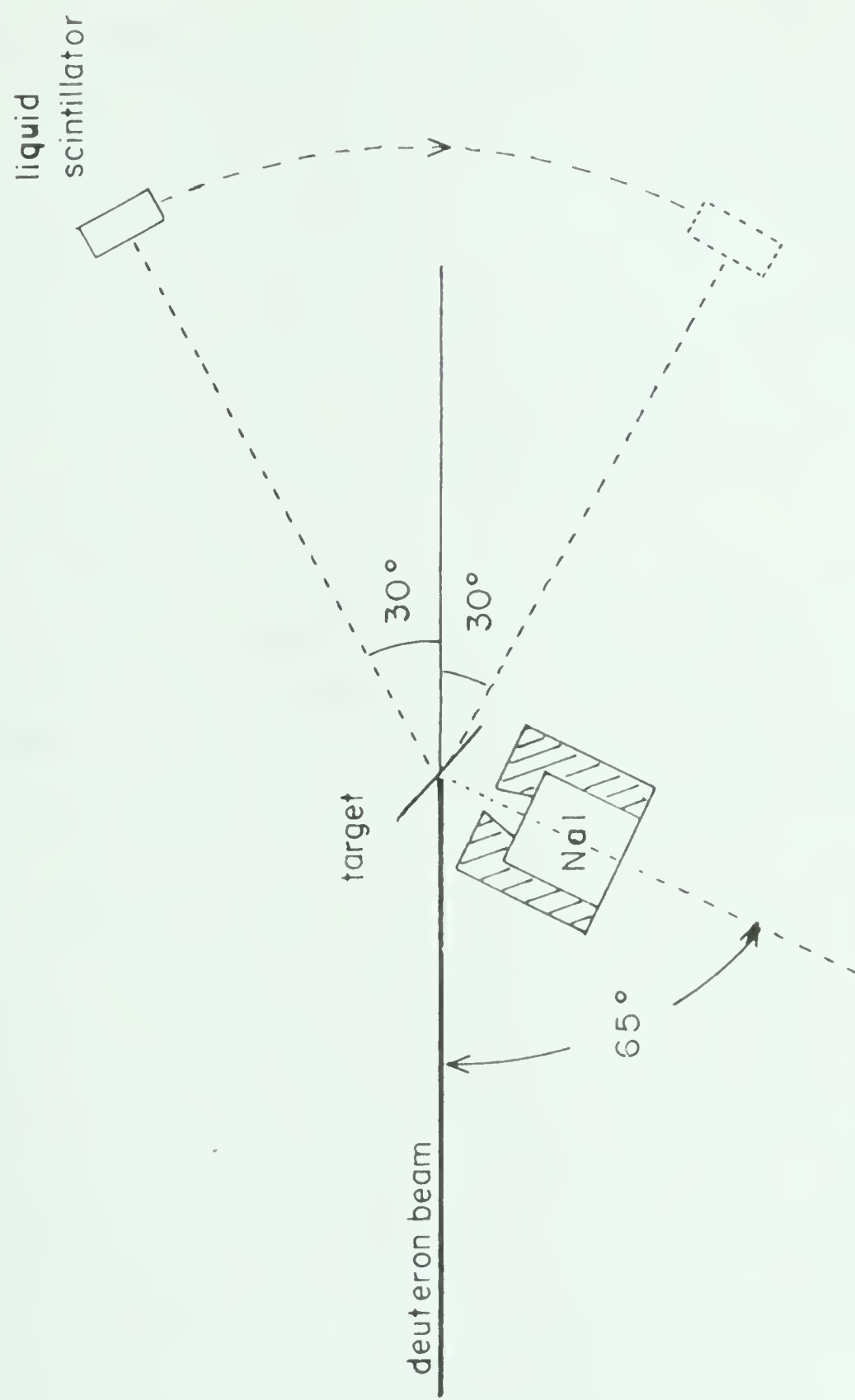


Figure 4-4 Experimental arrangement of the NaI gamma counter and the liquid scintillator neutron counter.

for gain shifts. Energy calibrations were obtained using RdTh and Na^{22} sources a few seconds after the beam had been switched off.

III. Experimental Spectra Obtained

Four gamma-neutron coincidence spectra were recorded with the single channel analyzer set to accept neutrons from the 6.48 Mev level of C^{11} . Runs I and II were performed with the neutron counter at 30° , and with a neutron flight path of 50 cm. Runs III and IV were performed with the neutron counter at 0° and -30° respectively, and with a 40 cm flight path. The total times required for runs I, II, III, and IV were approximately 1, 2, 5, and 2 hours respectively.

Figure 4-5a shows a typical ungated $\text{NaI } \text{B}^{10} + \text{d}$ spectrum; the major contributions are from gamma-rays of energies of approximately 4.5, 6.5, and 9 Mev. Figure 4-5b shows the coincident gamma-ray spectrum obtained during run I; 6.48 Mev gamma-rays are most intense. There is also a 4.3 Mev line, and some counts in the 7 to 10 Mev region. The counts in the 7 to 10 Mev region can be attributed to the $\text{B}^{10}(\text{d}, \text{p}, \gamma)\text{B}^{11}$ reaction, and therefore are purely random. The width of the 6.5 and 4.3 Mev lines is not as narrow as it should be for pure gamma-rays indicating that there has been some gain shift during the experiment. The gamma-ray bias energy was approximately 2 Mev. Below 2 Mev a rather high counting rate was observed, partly caused by iodine-neutron reactions in the crystal. The total ungated counting rate from the NaI counter was approximately 5000 per second between 1 and 10 Mev.

Figure 4-5c shows a gamma-neutron coincidence spectrum recorded with the single-channel analyzer set to accept neutrons only from the 4.26 and 4.75 Mev levels of C^{11} . All other experimental conditions were identical to the conditions

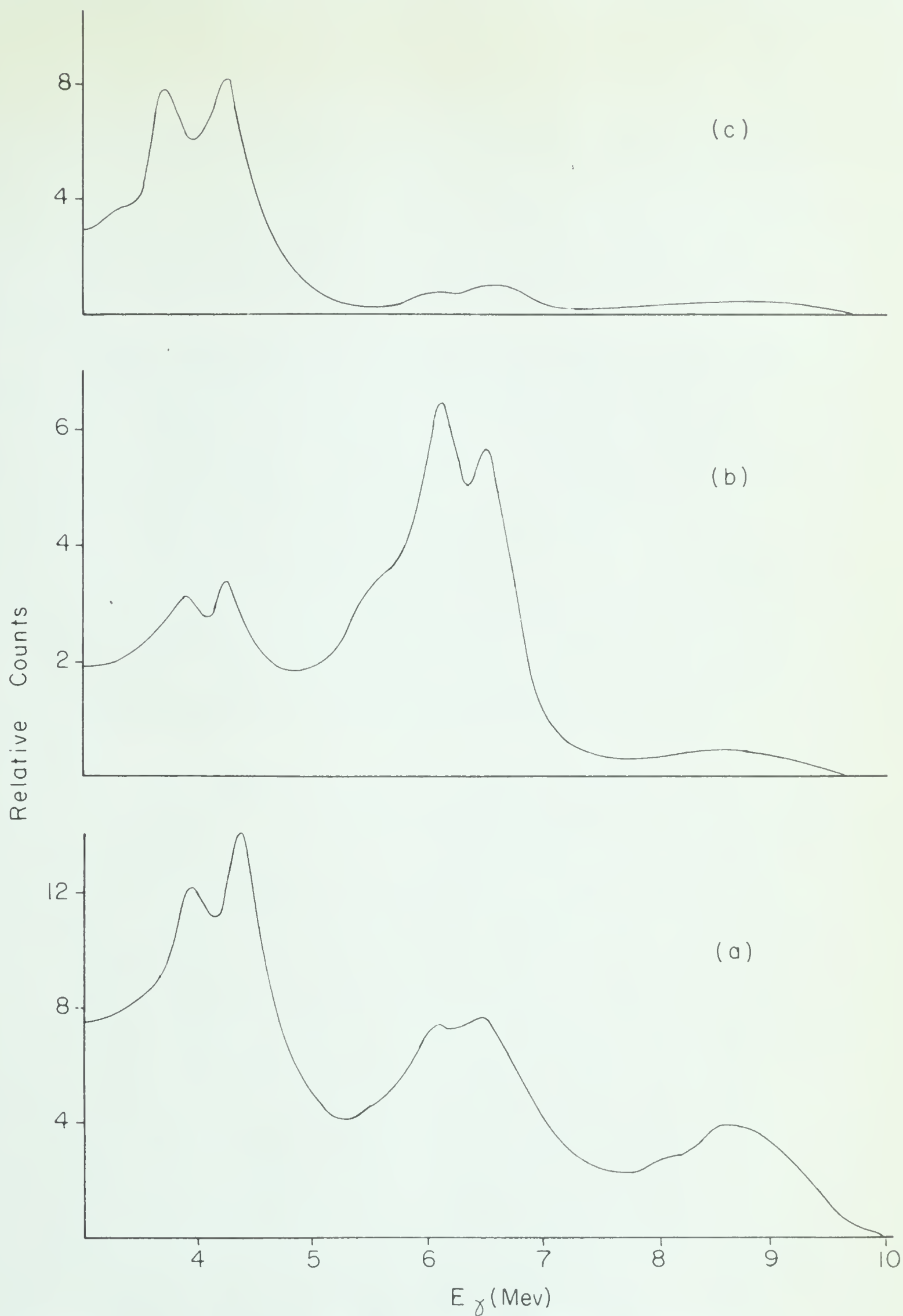


Figure 4-5 (a) $B^{10} + d$ ungated gamma-ray spectrum.
 (b) Gamma-rays in coincidence with neutrons leading to the 6.48 Mev level in Cl^{35}
 (c) Gamma-rays in coincidence with neutrons leading to the 4.26 and 4.75 Mev levels of Cl^{35} .

for run I. The spectrum is nearly that of a pure 4.26 Mev gamma-ray since the 4.26 Mev state in C^{11} is fed much more strongly than is the 4.75 Mev level, and the 4.26 Mev state decays directly to the ground state (Do 61). There are also random contributions to the spectrum in the 5 to 10 Mev region.

To reduce the random counting rate, runs II, III, and IV were performed with the total counting rate from the NaI crystal reduced by a factor of 2, to approximately 2500 per second between 1 and 10 Mev. The gamma-neutron coincident counting rate was found to be reduced by a factor of 4 from the coincident counting rate in run I. However, the random counting rate was found to be reduced by nearly a factor of 16. Figure 4-6 shows the resulting coincidence gamma-ray spectra recorded during runs II and IV. For runs II, III, and IV the 4.26 and 6.5 Mev gamma shapes agreed well with the expected shapes for pure gamma-rays.

For run III, taken with the neutron counter at 0° , the relative intensity of the 4.26 Mev gamma-ray in the spectrum was approximately a factor of 2 higher than the relative intensity of this gamma-ray in runs II and IV, taken with the neutron counter at 30° and -30° respectively. Analysis of the neutron time-of-flight spectrum on the 100 channel pulse-height analyzer showed that neutrons leading to the 6.48 Mev level were not being cleanly selected from neutrons leading to the 4.26 and 4.75 Mev levels. The ratio of the yield of neutrons to the 6.48 Mev state to the yield to the 4.26 and 4.75 Mev states decreases by nearly a factor of 2 between 30° and 0° . Slight overlapping of the neutron lines therefore allowed a higher proportion of 4.26 and 4.75 counts in the 6.48 gating pulses at 0° than at 30° . A contribution of only 5% of the counts in the 6.48 line from neutrons leading to the 4.26 and 4.75 Mev states would explain the unusually low 6.48/4.26 branching

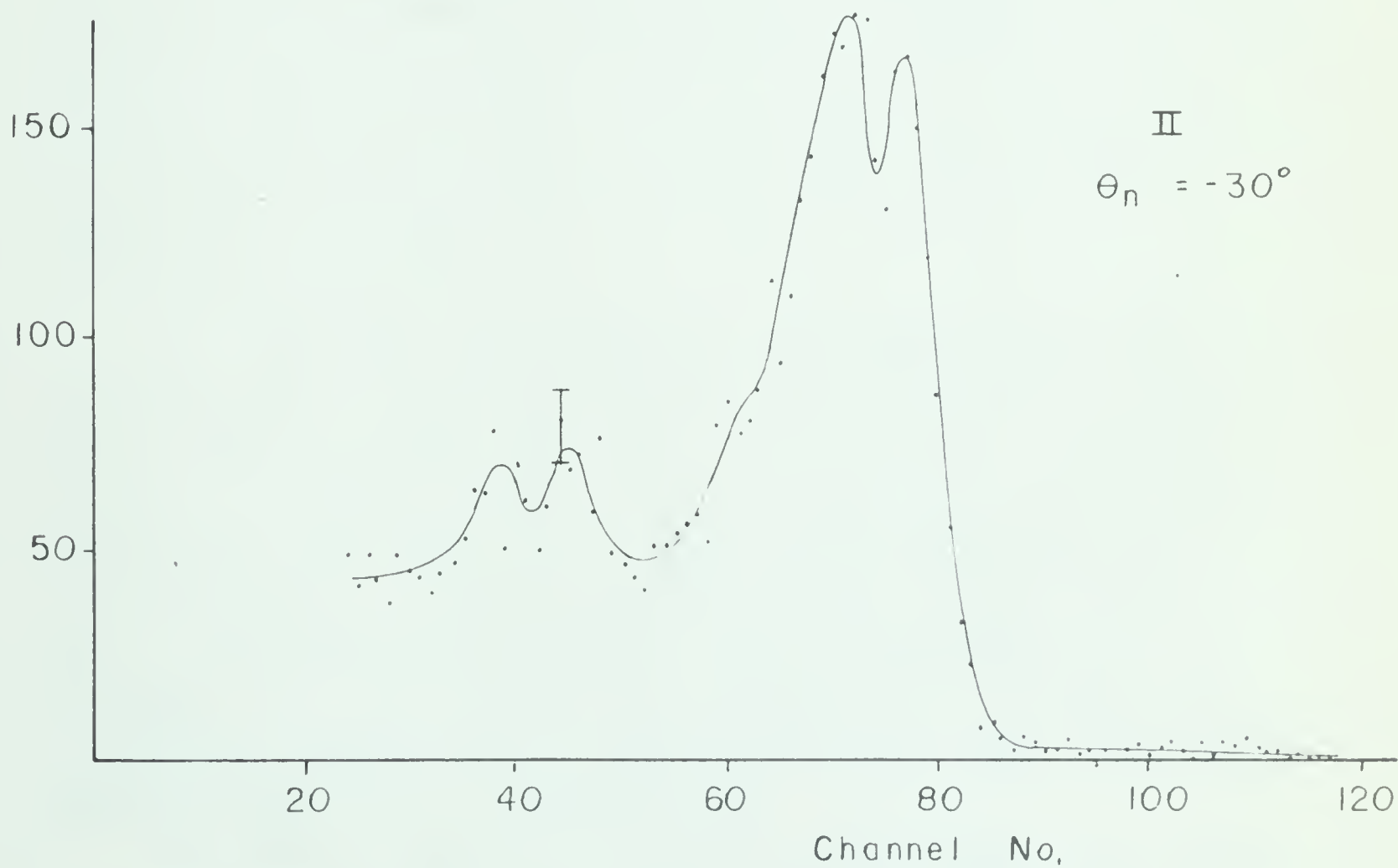
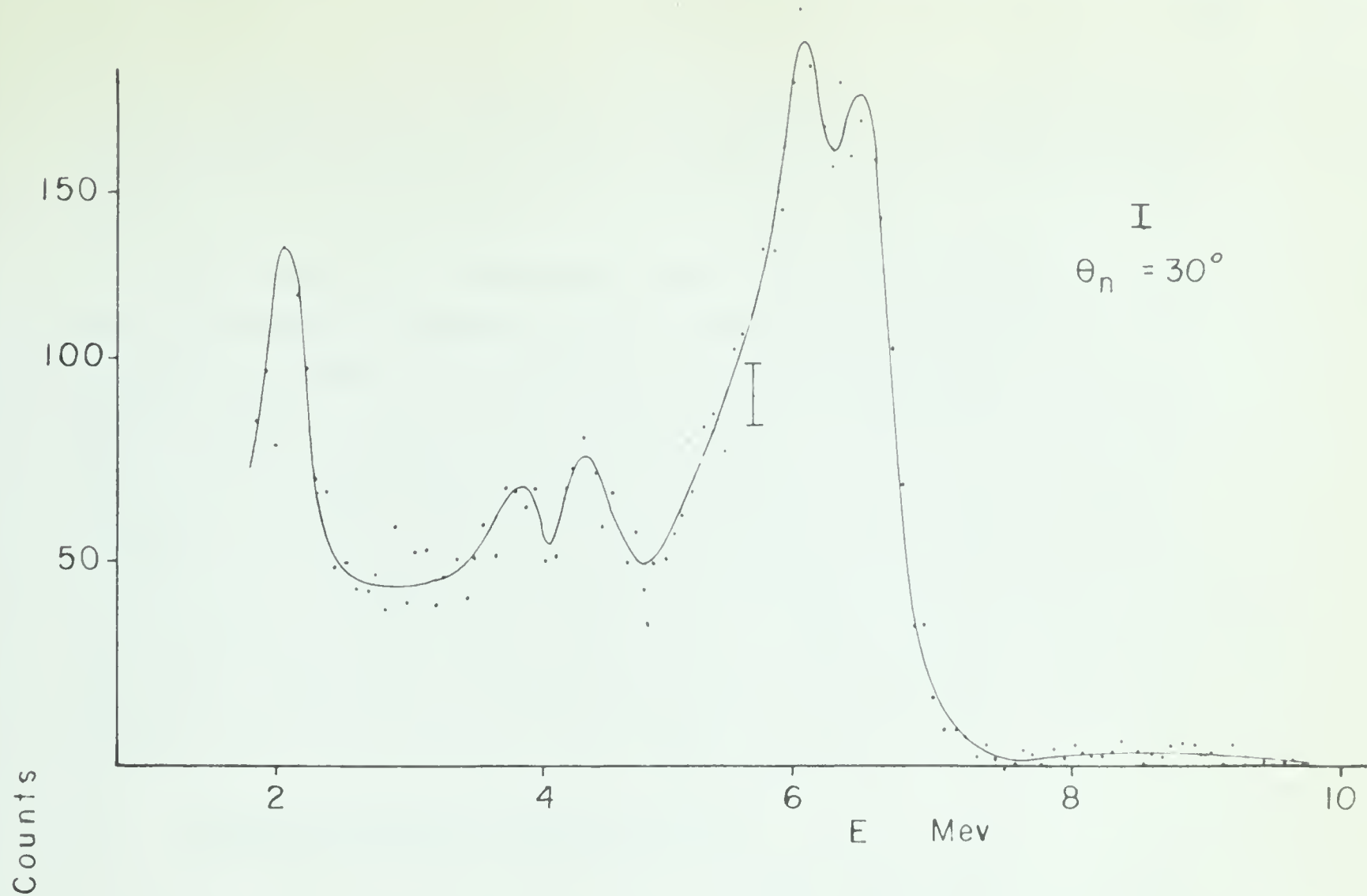


Figure 4-6 Gamma-rays in coincidence with neutrons leading to the 6.48 Mev level of Cl^{35} .

ratio observed in run III. The results of run III were therefore discarded in the calculation of the branching ratio.

It should be mentioned that the most probable sources of experimental error tend to decrease the observed 6.48/4.26 branching ratio. The effect of a high random counting rate, caused by too high a counting rate in the NaI counter and too poor a coincidence resolving time, is evident in run I. Spurious counts in the neutron gating spectrum, whether caused by incomplete gamma-ray suppression or by incomplete separation of neutrons from the 6.48 Mev state from neutrons to lower adjacent states, will also enhance the 4.26 Mev gamma-ray counts in the coincidence spectrum.

IV. Branching Ratio Calculations

In order to calculate the 6.48/4.26 branching ratio it was first necessary to estimate and subtract the random counts, the main source of which was the $B^{10}(d,p\gamma)B^{11}$ reaction (Be 55, Sa 55). The next step was to determine the response of the NaI crystal to 4.26 and 6.48 Mev gamma-rays; knowing this, the branching ratio could be calculated directly.

To facilitate the analysis, the energy scale was divided into the three intervals extending from 3 to 4.85 Mev, 4.85 to 7.4 Mev, and from 7.4 to 10 Mev. Counts in the 7.4 to 10 Mev region were all considered to be random counts and were used as the basis for normalization in determining the number of random counts between 3 and 7.4 Mev. The random pulse-height distribution spectrum was assumed to be identical to the ungated $B^{10} + d$ gamma-ray spectrum. Details of the calculations for each coincidence spectrum are given in Appendix VI.

The above calculation should over-estimate the number of random counts in the 6.5 Mev region, and therefore

predict too low a 6.48/4.26 branching ratio, since it assumes that random counts are as probable from the decay of the 6.48 Mev state as from any other channel. In order for decays from the 6.48 Mev state to give random counts, there must be more than one such decay within the coincidence resolving time; the probability for this should be strongly reduced from the probability of occurrence of an independent event within the 0.1 μ second resolving time. Therefore, the random counts have also been calculated by assuming that the random pulse height distribution spectrum is identical with the ungated $B^{10} + d$ spectrum after subtraction of contributions from 6.5 Mev gamma-rays (See appendix VI). However, the predicted branching ratio is not significantly changed by this assumption regarding random counts.

The experimental results are summarized below; details of the data and analysis are given in Appendix VI. The second row in the table indicates the importance of the random counts in the branching ratio calculations; the only difference between runs I and II is a reduction in the random counting rate, yet the apparent 6.48/4.26 branching ratio increases by nearly a factor of 2 between runs I and II.

	Run No.		
	I	II	IV
Θ_n laboratory system	30°	30°	-30°
Branching ratio, assuming 0 randoms	3.6	5.8	6.4
Random counts (3 - 10 Mev)	2230 ± 100	387 ± 50	413 ± 50
Genuine coincidence counts	5520 ± 150	4410 ± 100	4171 ± 100
6.48/4.26 corrected branching ratio	7.5 ± 2	7.4 ± 1.5	9.3 ± 1.5

The branching ratios obtained after subtraction of the random counts are in agreement. The mean of the determinations gives a value for the branching ratio of the 6.48 Mev state to ground relative to the 6.48 to the 4.26 Mev state of $8 \pm 1 : 1$.

V. Discussion

(a) Angular Distribution of the Gamma-rays

In the measurement of neutrons from the 6.48 Mev state of C^{11} , Neilson et al (Ne 60) observed that the neutron-gamma angular correlation was isotropic, an indication that the angular distribution of the intense 6.48 Mev ground state transition is isotropic. The transition to the 4.26 Mev state is much less intense; this transition could then possibly have a strong angular distribution. Since the 6.48/4.26 branching ratios observed at neutron counter angles of -30° and 30° agreed to within experimental error, a strong angular distribution is not likely. Probably the observed branching ratio of the 6.48 to ground to the 6.48 to 4.26 Mev state of $8 : 1$ is nearly independent of angle.

The argument that the angular distributions of the gamma-rays from the decay of the 6.48 Mev state are nearly isotropic can be strengthened by assuming that the 6.48 Mev state is formed by simple Butler stripping in the $B^{10}(d,n)C^{11}$ reaction. In this case, the direction of the incident proton is uniquely defined for a given neutron angle by the relationship

$$\tan \alpha = \frac{k_n \sin \Theta}{k_d - k_n \cos \Theta}$$

where k_n and k_d are the center of mass wave numbers for the neutron and deuteron respectively, and Θ is the center of mass neutron angle. In the present experiment, $E_d = 1.25$ Mev (center of mass), $E_n = 1.4$ Mev, and $\Theta_n = 34^\circ$, from which $\alpha = 48^\circ$ in the center of mass.

With the neutron counter at -30° in the laboratory system, the angle between the incident proton direction and the angle at which the gamma-ray was detected is 163° in the center of mass system; with the neutron counter at $+30^\circ$, the corresponding angle between the proton and gamma direction was 67° , again in the center of mass. If the decay process can be considered the result of a (p,γ) reaction, then symmetry about 90° can be assumed, and the experiment consists of branching ratio measurements at angles of 17° and 67° with respect to the incident proton direction. The branching ratios at these two angles should differ if the gamma-rays have anisotropic angular distributions.

(b) Theoretical Branching Ratios

Kurath (Ku 57) has calculated the M1 and E2 transition probabilities for several nuclei in the ℓ_p shell using the independent particle model. For M1, Kurath used $\Gamma(M1) = 2.76 \times 10^{-3} E^3 \Lambda(M1)$ where the "transition strength", $\Lambda(M1)$, is given by

$$\Lambda(M1) = \left(\frac{2J_f + 1}{2J_i + 1} \right) \frac{|\langle J_f^m | \mu | J_i^m \rangle|^2}{(J_i^m | J_f^m)^2}$$

Kurath gives values of $\Lambda(M1)$ as a function of the strength of the spin-orbit coupling, a/K , for $5/2$ to $7/2$ transitions. For $7/2$ to $5/2$ transitions, it is necessary to interchange J_f and J_i in the expression for the transition strength. Since μ is a Hermitian operator,

$$|\langle J_f^m | \mu | J_i^m \rangle|^2 = |\langle J_i^m | \mu | J_f^m \rangle|^2.$$

From the relations given in Rose (Ro 57)

$$C(j_1 j_2 j_3; m_1 m_2 m_3) = (-1)^{j_2 - m_2} \left(\frac{2j_3 + 1}{2j_1 + 1} \right)^{1/2} C(j_3 j_2 j_1; -m_3 m_2 -m_1)$$

and

$$C(j_1 j_2 j_3; m_1 m_2 m_3) = (-1)^{j_1 + j_2 - j_3} C(j_1 j_2 j_3; -m_1, -m_2, -m_3)$$

$$\text{then } \Lambda(M1)_{j_f \rightarrow j_i} = \frac{2j_i + 1}{2j_f + 1} \Lambda(M1)_{j_i \rightarrow j_f}$$

$$\text{that is, } \Lambda(M1)_{\frac{7}{2} \rightarrow \frac{5}{2}} = \frac{3}{4} \Lambda(M1)_{\frac{5}{2} \rightarrow \frac{7}{2}}$$

$$\text{Similarly, } \Lambda(E2)_{\frac{7}{2} \rightarrow \frac{5}{2}} = \frac{3}{4} \Lambda(E2)_{\frac{5}{2} \rightarrow \frac{7}{2}}$$

The expected transition widths for ground state E2 transitions from the $7/2^-$ 6.48 Mev level in C^{11} can now be compared directly with the transition widths for M1 transitions from the 6.48 Mev state to the $5/2^-$ 4.26 Mev state as a function of the spin-orbit coupling coefficient, a/K . For all a/K given in the tables of Kurath, except for $a/K = 4.5$, where the M1 transition probability is zero, the M1 transition probability between the $7/2$ and $5/2$ states of C^{11} is much greater than the E2 transition probability between these two states. The E2 transition probability from the $7/2$ to the $5/2$ state has therefore been neglected. Values of the E2 ground state transition widths from the 6.48 Mev level of C^{11} , M1 transition widths from the 6.48 to the 4.26 Mev level, and the resulting branching ratios are given in the following table. The theoretical branching ratios for the decay of the mirror 6.76 Mev state in B^{11} are approximately 10% higher.

a/K	$\Lambda(E2)$	$\Gamma(E2)$ ev	$\Lambda(M1)$	$\Gamma(M1)$ ev	$\frac{\Gamma(E2)}{\Gamma(M1)}$
0	0.175	.0160	.06	.00181	8.85
1.5	0.180	.0165	.075	.00226	7.3
3.0	0.167	.0153	.052	.00157	9.75
4.5	0.120	.011	0.00	0.00	∞
6.0	0.078	.00716	.082	.00248	2.89
7.5	0.050	.0046	0.28	.00846	.54

The theoretical branching ratios agree well with the observed ratio of 8:1 for any of the a/K values less than 4.5.

Radiative widths for the extreme independent particle model of Weisskopf are $\Gamma(E2) = 1 \times 10^{-2}$ ev and $\Gamma(M1) = 40 \times 10^{-2}$ ev giving $\Gamma(E2)/\Gamma(M1) = .04$. The values have been taken from the nomogram given by Wilkinson (Wi 60).

Collective model calculations have been made by D. W. Braben of this laboratory, who assumes that the C^{11} nucleus has the same quadrupole moment as the B^{11} nucleus and that the ground, 4.26, and 6.48 Mev states of C^{11} can be considered to be the first three states in a $K = 3/2$ band. The resulting ratio of $\Gamma(E2)/\Gamma(M1)$ is 0.36.

The predictions of the independent particle model, the collective model, and the Weisskopf model are summarized below. For the independent particle model calculation, the parameter a/K has been assumed to be one of the three values 0, 1.5, or 3.

	Collective Model	I.P.M.	Weisskopf Model	Observed
6.48 $\rightarrow$ Gnd $\Gamma(E2)$	3.2×10^{-2} ev	$1.53 - 1.60 \times 10^{-2}$ ev	1×10^{-2} ev	--
6.48 $\rightarrow$ 4.26 $\Gamma(M1)$	8.7×10^{-2} ev	$1.6 - 2.3 \times 10^{-3}$ ev	40×10^{-2} ev	--
$\Gamma(E2)/\Gamma(M1)$	0.36	7.3 - 9.75	0.04	8 ± 1

Of the three models, only the independent particle model gives a branching ratio in agreement with experiment. Since the radiative transition widths offer reasonably sensitive tests of nuclear wave functions (Ku 57), probably the independent particle model is the only one of the three models which can be successfully fitted to the low-lying states of C^{11} . It has been pointed out, however (J. A. Kuehner, private communication) that the close agreement of the independent-particle shell model prediction to the experimentally observed branching ratio may be fortuitous. The nuclear wave functions of Kurath, on which the transition widths are based, predicts the lowest $7/2$ and $5/2$ energy levels in an $A = 11$ nucleus to be nearly coincident. This gives rise to an abnormally small $\Gamma(M1)$ transition width, which produces a high value for the $\Gamma(E2)/\Gamma(M1)$ ratio.

The experimentally determined branching ratio is in reasonable agreement with the measurement of Ferguson et al at Chalk River, and in disagreement with the branching ratio determined by Green et al at Liverpool.

CHAPTER V. A SURVEY OF THE REACTION $F^{19}(d,n)Ne^{20}$

I. Introduction

Preliminary time-of-flight measurements, using both pulsed beam and neutron-gamma coincidence techniques, have been made on neutron groups produced in the $F^{19}(d,n)Ne^{20}$ reaction. Although the data obtained are not adequate for detailed analysis, they do show that the experiment is both interesting and feasible.

In the last few years shell model and collective model calculations have been successful in predicting the spins and parities of low-excited states of nuclei in the region of Ne^{20} . Recently, the excited states of Ne^{20} up to an excitation of 9 Mev have been studied intensively using the reactions $Ne^{20}(p,p'\gamma)Ne^{20}$ and $Cl^{12}(Cl^{12},He^4)Ne^{20}$. (Cl 61, Li 61, Go 69, Ku 62). This work has shown that the collective model gives a good account of the properties of the low-lying states of Ne^{20} . An energy-level diagram, taken from the work of Litherland et al is shown in Figure 5-1. Because of the high energy level density, not all of the observed levels in the energy region above 7 Mev have been included.

Excited states of Ne^{20} have been studied also by means of the reactions $F^{19}(p,\gamma)Ne^{20}$, $Na^{23}(p,\alpha)Ne^{20}$ (Bu 57), $O^{16}(\alpha,\alpha')O^{16}$ (Ca 53, Mc 60b), and $F^{19}(d,n)Ne^{20}$. As indicated by the energy level diagram, excited states of Ne^{20} between 19 and 13 Mev are easily accessible by means of the $F^{19}(d,n)Ne^{20}$ reaction. Because of experimental difficulties in resolving neutron groups by conventional neutron spectroscopy, nearly all reported work in this energy region has involved observing gamma-

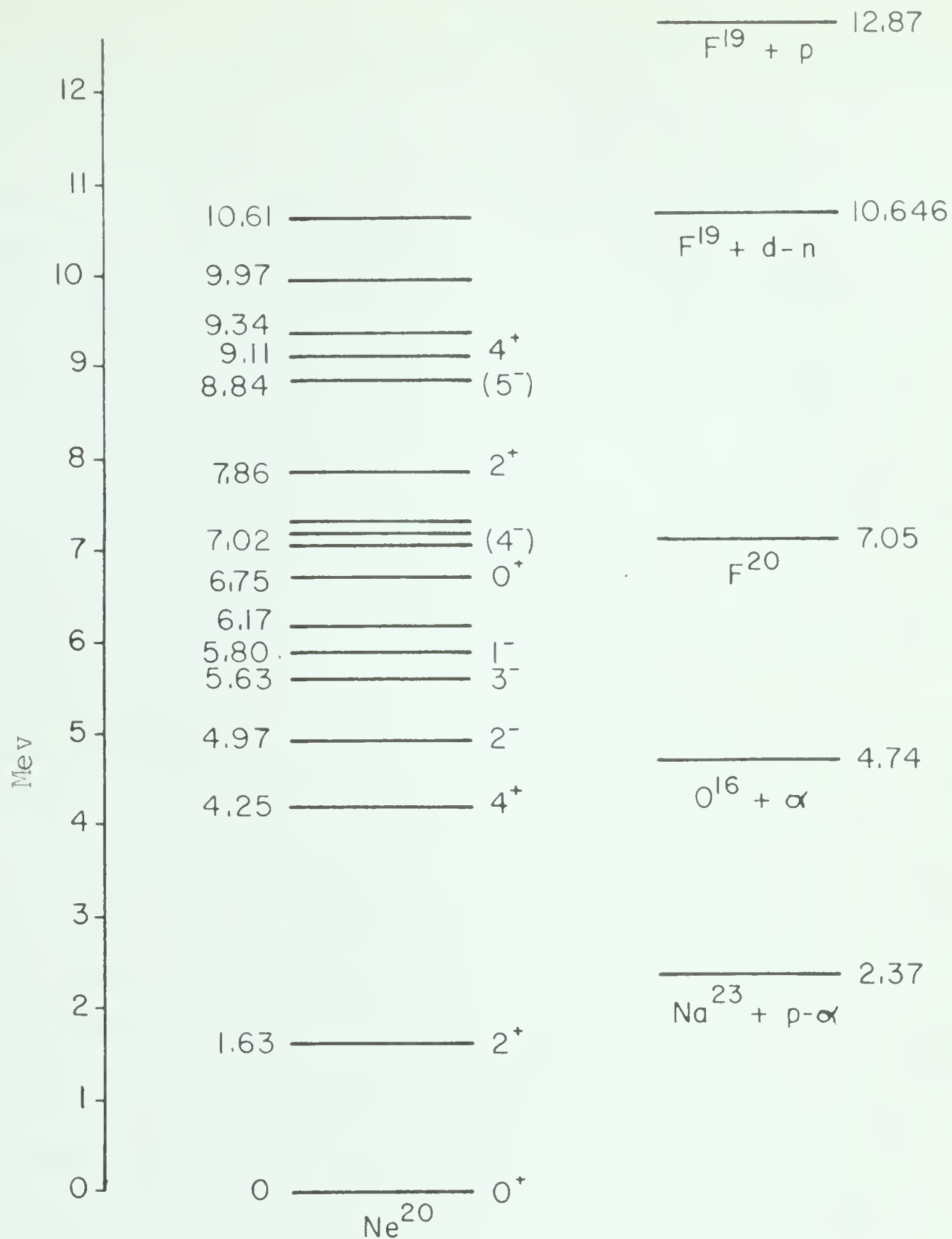


Figure 5-1 Energy levels of Ne^{20} .

rays produced in the $F^{19}(d,n\gamma)Ne^{20}$ reaction. Gamma-rays from Ne^{20} are likely to be observed only when alpha-emission to $O^{16} + \alpha$ is inhibited. Between the threshold energy of 4.745 Mev and 10.89 Mev levels of Ne^{20} which have even-minus or odd-plus spin parity combinations are inhibited from decaying by alpha-emission to $O^{16} + \alpha$, and so should be observed in the $F^{19}(d,n\gamma)Ne^{20}$ reaction. Above 10.89 Mev states of Ne^{20} can break up by alpha-emission to the second excited level of O^{16} (a 3^- state). The α -decay of $T = 1$ levels of Ne^{20} to $T = 0$ states in O^{16} should also be inhibited. The lowest $T = 1$ state in Ne^{20} is believed to be the 9.97 Mev state (Be 55). The isobaric spin selection rule, together with the small alpha-particle barrier penetration, should allow decay predominantly by gamma emission from states in Ne^{20} as high as 12.2 Mev (Ra 60).

Two experimental techniques have been used to study the gamma radiation produced in the $F^{19}(d,n\gamma)Ne^{20}$ reaction. Bent et al, (Be 55), using a magnetic pair spectrometer, observed states in Ne^{20} at excitation energies of 9.34, 9.97, 10.61, and 11.51 Mev, all tentatively with 1^- or 2^- spins. Rabson et al (Ra 60), also using a pair spectrometer, reported gamma-emitting states in Ne^{20} at excitations of 7.26, 9.22, 9.98, 11.31, and 12.22 Mev. Probably the 9.22 and the 9.98 Mev states are those previously reported at 9.34 and 9.97 Mev by Bent et al. Butler, using a gamma-ray threshold technique, observed states in Ne^{20} at excitation energies of 11.11, 11.19, 11.33, 11.42, 11.69, 11.97, 12.17, 12.27, and 12.51 Mev.

Because the consistency in the gamma-ray work described in the preceding paragraph is not good, neutron time-of-flight measurements on neutron groups leading to states in Ne^{20} between 9 and 13 Mev would be particularly interesting. By using neutron-gamma coincidence techniques, it should be possible to

check directly on the experiments of Bent, Rabson, and Butler. A comparison of time-of-flight neutron spectra obtained when using a pulsed beam and spectra recorded when using the coincidence method should also give direct information on the decay of the levels.

Although the $F^{19}(d,n)Ne^{20}$ reaction provided some of the earliest information on the positions of the low-lying levels of Ne^{20} (Aj 55), there have been only a few measurements on neutron groups produced in this reaction. Calvert et al (Ca 55) using a deuteron energy of 9 Mev, obtained good stripping angular distributions for the ground and the first excited states of Ne^{20} . Morita and Takeshita (Mo 58a), at a deuteron energy of 2.17 Mev, did not obtain good stripping patterns, and their data indicated the presence of weak neutron groups inconsistent with the level scheme for Ne^{20} shown in Figure 5-1. Benenson et al (Be 61), at a deuteron energy of 3.57 Mev, observed energy levels in Ne^{20} at 1.63, 4.25, 4.97, 5.63, and 6.75 Mev; good fits to theoretical stripping angular distributions were observed only for the ground, 1.63, and 6.75 Mev levels. The above experiments employed nuclear emulsion techniques, except for one spectrometer measurement by Benenson of neutrons leading to the 6.75 Mev state of Ne^{20} . Time-of-flight measurements on neutron groups produced in the $F^{19}(d,n)Ne^{20}$ reaction were, therefore, of interest in order to compare the results with the results of the nuclear emulsion work.

The study of neutron groups produced in the reaction $F^{19}(d,n)Ne^{20}$ might also provide a check on the effect of the reaction Q on the stripping mechanism for (d,n) reactions, since both high-Q (up to 10.646 Mev) and low-Q levels are available. Wilkinson (Wi 58) has suggested that at low bombarding energies angular distributions for high-Q reactions would be greatly distorted from recognizable patterns. A

comparison of angular distribution measurements from high and low-lying states of Ne^{20} would, therefore, be of interest.

Two major experimental difficulties were expected. First, some states in Ne^{20} break up directly via 3-body break-up; that is, the reaction $\text{F}^{19} + \text{d} \rightarrow \text{O}^{16} + \text{n} + \alpha$ really occurs. In this event neutrons leading to a given state in Ne^{20} do not have a discrete energy, and contribute to the background in the time-of-flight spectrum, making the measurement of neutron spectra from other states difficult. For example, Kuehner and Almqvist (Ku 61) reported that when a spectrometer selected alpha-particles feeding the 5.63 Mev state of Ne^{20} , Ne^{20} recoils of appropriate momentum were observed as well as peaks caused by break-up into O^{16} and He^4 ; with the 5.80 Mev state selected, O^{16} and He^4 recoils were observed but no significant yield of Ne^{20} recoils.

The second difficulty was caused by the high Coulomb barrier (about 3 Mev) and the consequently low expected yield of neutrons from the $\text{F}^{19}(\text{d}, \text{n})\text{Ne}^{20}$ reaction at the deuteron energies available. Even at 3.57 Mev, Benenson et al noted a scarcity of counts produced in the $\text{F}^{19}(\text{d}, \text{n})\text{Ne}^{20}$ reaction. It was hoped that the neutron yield at a deuteron energy of 2 Mev would be adequate. An estimate of the penetration parameter $\frac{P}{A_1^2}$, using "Graphs of Coulomb Functions" (Sh 53) indicated that the penetrability for absorption of protons into F^{19} should change by a factor of 10 between 1 and 2 Mev.

II. Experimental

(a) Neutron time-of-flight spectra obtained.

Initial runs were made using a pulsed 1.5 Mev deuteron beam, and a neutron flight path of 3 meters. The fluorine target, prepared by evaporating CaF_2 onto 0.001 inch thick platinum backing, was approximately 100 kev thick, measured at the 873 kev resonance of $\text{F}^{19}(\text{p}, \alpha\gamma)\text{O}^{16}$. For the $\text{F}^{19}(\text{d}, \text{n})\text{Ne}^{20}$

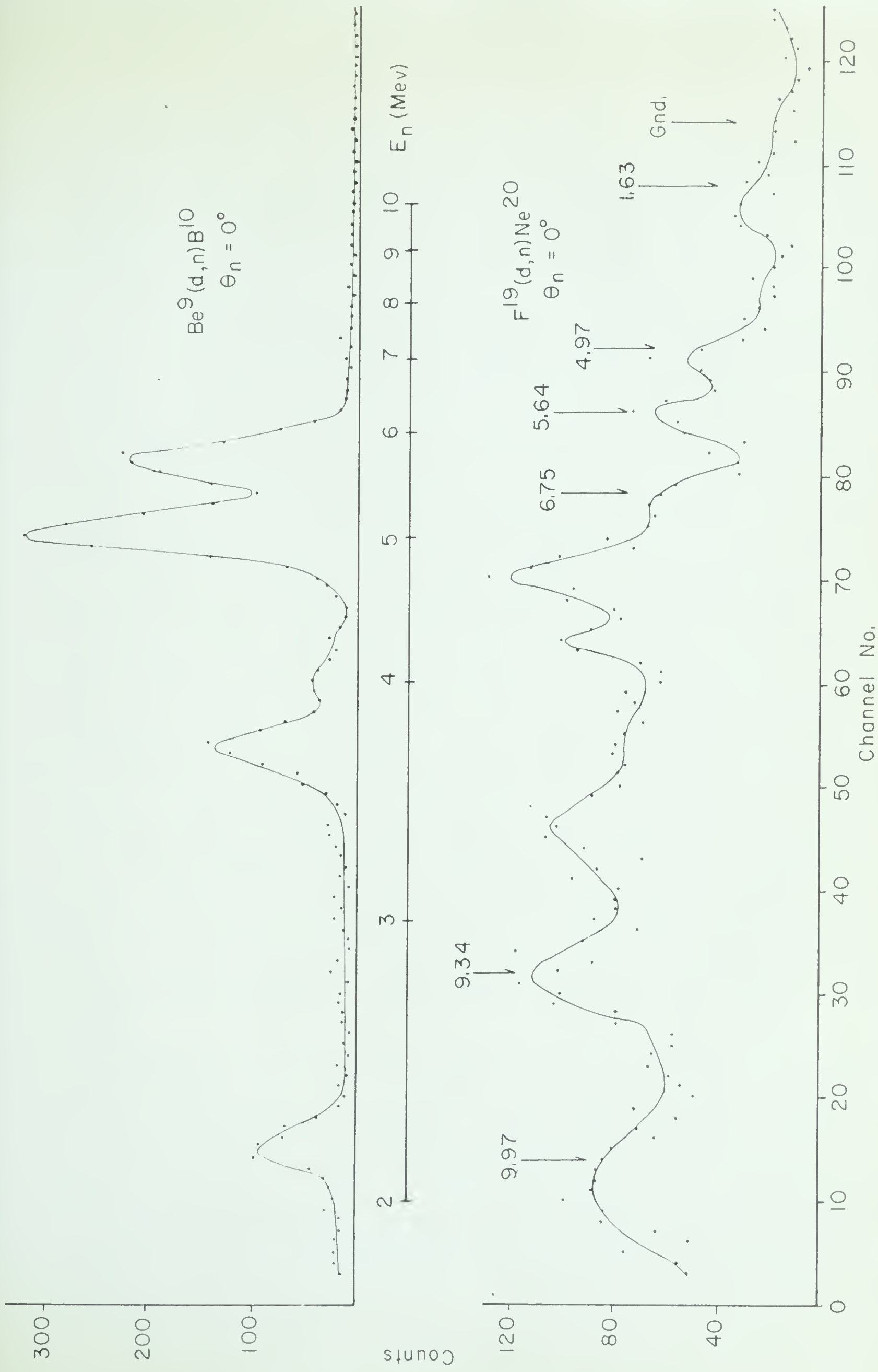


Figure 5-2 Pulsed beam neutron time-of-flight spectra. $E_d = 1.5$ Mev, $S_n = 3$ meters

pulsed beam runs the target was mounted at 60° to the incident beam, giving an effective target thickness of approximately 200 kev. The $\text{Be}^9(\text{d},\text{n})\text{B}^{10}$ reaction was used to provide comparison spectra; the beryllium target was 40 kev thick for 1 Mev protons.

Figure 5-2 shows typical spectra, taken with the counter at 0° to the incident deuteron beam. The $\text{Be}^9(\text{d},\text{n})\text{B}^{10}$ spectrum took 7 minutes to record; the $\text{F}^{19}(\text{d},\text{n})\text{Ne}^{20}$ required 40 minutes, an indication of the low neutron yield from the $\text{F}^{19}(\text{d},\text{n})\text{Ne}^{20}$ reaction. Neutron groups leading to the levels in Ne^{20} at excitation energies of 1.63, 4.97, 5.64, 6.75, 9.34, and 9.97 Mev have been tentatively identified. The arrows indicate the expected line positions for the given $\text{F}^{19}(\text{d},\text{n})\text{Ne}^{20}$ neutron groups with respect to the $\text{Be}^9(\text{d},\text{n})\text{B}^{10}$ spectrum, and coincide reasonably well with the observed line positions. The time scale for Figure 5-2 is 0.83 nsecs per channel. Neutron groups leading to the ground state of Ne^{20} and to the 4.25 Mev level cannot be identified in the spectrum; there is, however, some evidence for these groups in Figure 5-3. No attempt has been made to identify neutron groups in the region of excitation of Ne^{20} from 7 to 9 Mev; probably the two peaks which appear immediately to the left of the 6.75 groups are due to several of the densely spaced levels from 7 to 8 Mev. The 9.97 Mev level appears well resolved, even though sitting above a high background, likely due to 3-body break-up. The extremely poor time resolution of neutrons leading to this state is caused by the thick target.

Figure 5-3 shows $\text{F}^{19}(\text{d},\text{n})\text{Ne}^{20}$ spectra recorded at counter angles of 0° , 30° , 60° , and 90° with respect to the incident beam. The deuteron energy was 1.5 Mev and the flight path 3 meters. The average time required per run was 40 minutes. The neutron groups are too poorly resolved and the statistics too poor for detailed analysis. The yield of neutrons leading to the 6.75 Mev level does decrease rapidly with increasing

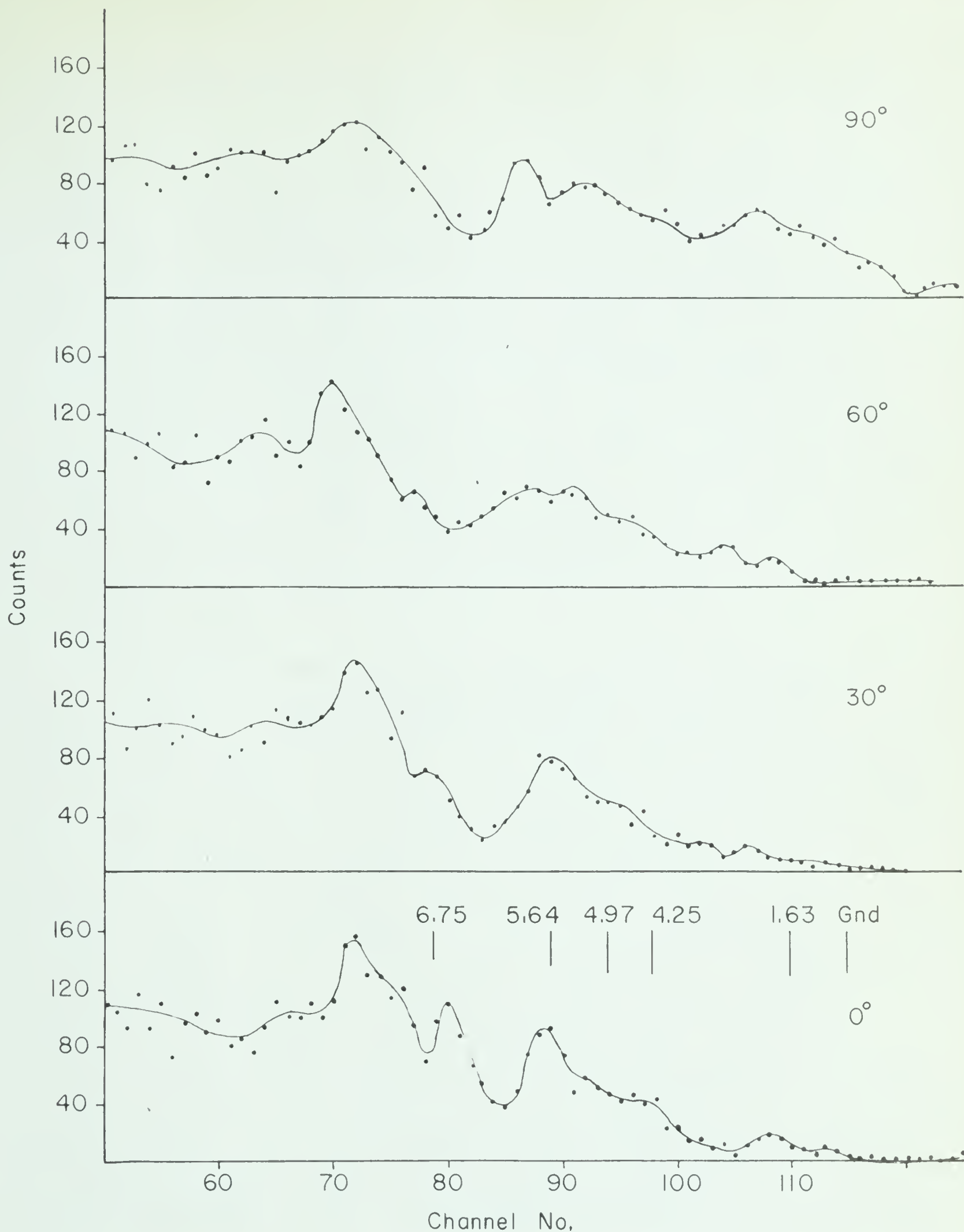


Figure 5-3 $F^{19}(d,n)Ne^{20}$ neutron spectra. $E_d = 1.5$ Mev, $S_n = 3$ meters

angle, in qualitative agreement with the work of Benenson et al, who found the angular distribution to the 6.75 Mev state to be well fitted by an $l_p = 0$ stripping curve. The yields to the ground state and to the first 4 excited states of Ne^{20} do not appear to decrease with increasing angle.

Figure 5-4 shows pulsed-beam spectra recorded at a deuteron energy of 2 Mev, and with a flight path of 2 meters. The time scale has been shifted in order to look for low energy neutron groups from the reaction $\text{F}^{19}(\text{d},\text{n})\text{Ne}^{20}$. The only significant line appearing to the left of the neutron group leading to the 9.97 Mev state of Ne^{20} occurs at a neutron energy of 1.7 Mev. This line was shown to be produced largely, if not entirely, by C^{12} contamination in the fluorine target. The relative intensity of this line was reduced by a factor of 3 when a spectrum was recorded using a newly evaporated fluorine target.

Preliminary neutron-gamma time-of-flight runs were made in an attempt to identify gamma-emitting states of Ne^{20} . Figure 5-5 shows $\text{Be}^9(\text{d},\text{n}\gamma)\text{B}^{10}$ and $\text{F}^{19}(\text{d},\text{n}\gamma)\text{Ne}^{20}$ neutron gamma coincidence spectra recorded at a deuteron energy of 1.8 Mev. The flight path was 1.5 meters, and the counter angle was 30° . The time required for the $\text{Be}^9(\text{d},\text{n}\gamma)\text{B}^{10}$ spectrum was 17 minutes; the $\text{F}^{19}(\text{d},\text{n}\gamma)\text{Ne}^{20}$ spectrum required 40 minutes. Neutron groups of energies 1.48, 2.44, and approximately 3.0 Mev appear in the $\text{F}^{19}(\text{d},\text{n}\gamma)\text{Ne}^{20}$ spectrum. 2.44 Mev is the expected energy for neutrons leading to the 9.97 Mev state of Ne^{20} observed by Bent et al (Be 55). The weak 3.0 Mev neutron group probably corresponds to neutrons leading to the 9.34 Mev state observed by Bent et al (Be 55); the neutron energy appears too low to lead to the 9.22 Mev state observed by Rabson et al (Ra 60). The 1.48 Mev neutron group probably leads to a state in Ne^{20} at 10.9 Mev excitation; alternatively,

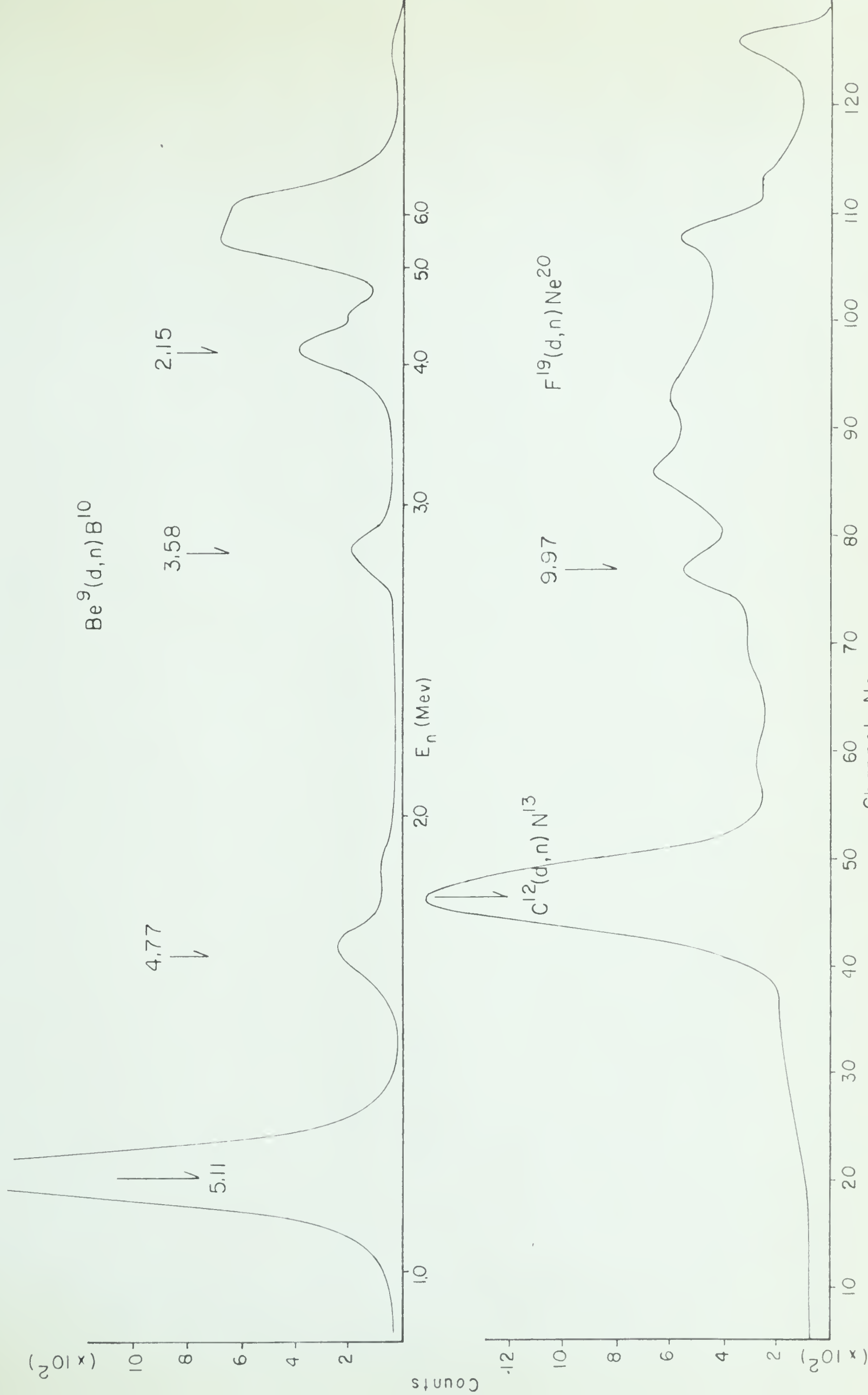


Figure 5-4 $\text{Be}^9(d,n)\text{B}^{10}$ and $\text{F}^{19}(d,n)\text{Ne}^{20}$ neutron spectra. $E_d = 2$ Mev, $S_n = 2$ meters, $\theta_n = 0^\circ$

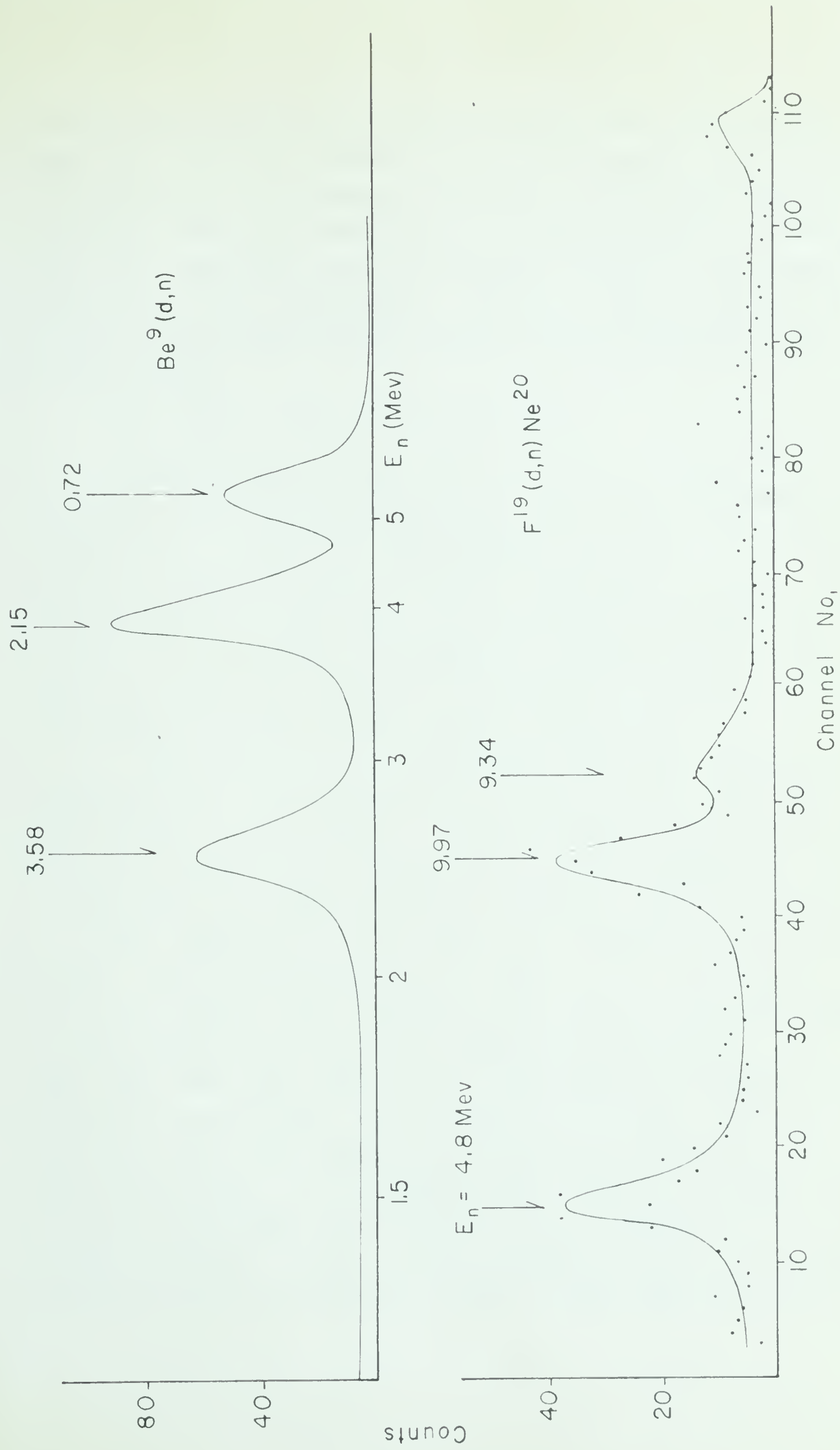


Figure 5-5 $\text{F}^{19}(d,n)\text{Ne}^{20}$ and $\text{Be}^9(d,n)\text{Be}^{10}$. Neutron-gamma coincidence spectra.

$E_d = 1.8$ Mev, $S_n = 1.5$ meters, $\theta_n = 30^\circ$

1.48 Mev is the neutron energy expected for $C^{12}(d,n)N^{13}$ neutrons. The only gamma-radiation produced by the reaction $C^{12}(d,n)N^{13}$ at low bombarding energy is 0.51 Mev annihilation radiation from the decay of N^{13} . Since N^{13} has a 10 minute half-life, neutrons from $C^{12}(d,n)N^{13}$ should not be emitted in coincidence with gamma-rays. However, the fact that the target was contaminated by carbon throws suspicion upon this neutron group.

(b) Target Carbon Contamination.

Several attempts were made to obtain carbon-free fluorine targets. Carbon contamination is especially troublesome when attempting to record neutron-gamma coincidence time-of-flight spectra, since the build-up of N^{13} results in a high 0.51 Mev annihilation radiation flux in the NE 102 gamma counter. In some of the badly contaminated fluorine targets, the counting rate from the decay of N^{13} accounted for nearly 1/4 of the total counting rate in the Ne 102 counter.

It was shown that if reasonable care were taken to prevent contamination, the evaporation process did not deposit significant carbon on the target. "Dummy" evaporation trials, during which no fluoride was introduced into the evaporator, did not contaminate the target backing. However, the fluorides used in target preparation are found to be slightly carbon contaminated; spectroscopically pure CaF_2 was not available. Fluorine targets were prepared using three fluorides supplied by the University of Alberta Chemistry Department; (1) extra-pure CaF_2 Chemical reagent, (2) BaF_2 Chemical reagent, and (3) pure precipitated CaF_2 , prepared in 1939. Of the three fluorides, the one prepared in 1939 was found to be the most free from carbon. The targets were tested for carbon contamination by bombarding them with 1.5 Mev deuterons with the beam current adjusted to give a total counting rate in the NE 102 counter of some 50,000 per second. After approximately 10

minutes, the beam was switched off and the counting rate due to N^{13} build-up was measured. The "cleanest" targets obtained, using the CaF_2 prepared in 1939, gave approximately 100 counts per second due to the N^{13} decay. That is, the carbon content relative to the first targets used was reduced by a factor of 100.

Neutron time-of-flight spectra were not recorded using these relatively carbon-free fluorine targets, as time was not available.

III. Conclusions

Only preliminary $F^{19}(d,n)Ne^{20}$ spectra were obtained. In addition to the expected experimental difficulties caused by a low counting rate and background produced by 3-body break-up processes, the targets used were seriously contaminated by carbon. However, it was possible to identify several neutron groups leading to states of Ne^{20} . Using a pulsed beam, neutron groups leading to the levels of Ne^{20} at 1.63, 4.97, 5.64, 9.34, and 9.97 Mev have been tentatively identified. The yield of neutrons leading to the 6.75 Mev level did decrease rapidly with increasing counter angle, in qualitative agreement with the work of Benenson et al. The resolution of neutron groups leading to the ground state and to the first 4 excited states was inadequate to determine the change of yield with increasing counter angle.

Preliminary neutron-gamma coincidence spectra indicated a reasonably intense neutron group leading to the 9.97 Mev state of Ne^{20} , and weaker group leading to the 9.34 Mev level. There is no evidence for the 7.26 Mev level observed by Rabson et al. There is some evidence for a gamma emitting state in Ne^{20} at 10.9 Mev excitation, although further runs are necessary to show that this neutron group is not caused by carbon contamination in the target. The nearest reported gamma

emitting state to 10.9 Mev is a state at an excitation of 11.11 Mev observed by Butler.

Further investigation of the $F^{19}(d,n)Ne^{20}$ reaction using both pulsed-beam and neutron-gamma coincidence techniques would be interesting, although because of the low neutron yield at energies below 2 Mev, a higher deuteron energy is desirable.

CHAPTER VI. ION PULSING

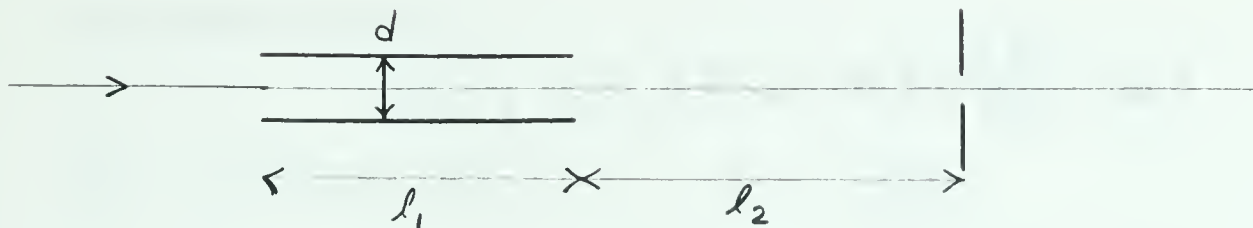
I. Introduction

Ion pulsing refers to the production of discrete bursts of ions of short time duration on a suitable target. In neutron time-of-flight work, the time of origin of neutrons from the target is then localized to the pulse duration. The neutron velocities, defined by the time required for neutrons to reach a detector situated at a known distance from the target, can then be measured.

This chapter describes attempts to develop a new ion pulsing system suitable for a Van de Graaff accelerator, and so to improve the performance of the neutron time-of-flight spectrometer. The usual methods of pulsing of ion beams from dc linear accelerators such as Van de Graaff generators will first be briefly described. The beam from a cyclotron is inherently pulsed, since the phase angle acceptable for successful ion acceleration is limited to a few degrees (Ne 60b). However, the pulsing mechanism is not readily controlled (Co 53, Ko 58, Ti 61).

(a) Beam chopping

Beam chopping is the oldest, and is still probably the most widely used method of ion pulsing. In fast neutron time-of-flight work, the beam chopping is done electrically rather than by mechanical devices. The beam is passed between two deflector plates between which a radio-frequency electric field is impressed. All ions except those which pass between the plates near zero field are swept off-axis and removed from the beam by collimating slits. A simplified theory of deflector plates is given below (Ne 60b).



The plate length and separation are given by l_1 and d respectively; the distance from the plates to the collimating slits is l_2 . An rf voltage $V_0 \sin 2\pi t/T$ is applied to the plates. Near zero phase, the field seen by an ion is

approximately $\xi = \frac{V_0}{d} \left[\frac{2\pi t}{T} + \delta \right]$ where $\delta = \omega t_0$ is the

phase at $t = 0$ when the ion enters the plates. The burst length, Δt_0 , is the time required for a beam of ions to be swept the distance Δy across the defining slits. The displacement from axis of an ion at the slits, $y_s = y_1 + y_2$, where y_1 and y_2 are the displacements incurred during the passage through l_1 and l_2 respectively.

In l_1 , $\ddot{y} = \frac{e\xi y}{m}$ and $\dot{y} = \int_0^{t_1} \frac{-e\xi y}{m} dt$ where $\dot{y}$ is the velocity component parallel to the electric field as the ion leaves the plates. Integrating,

$$\dot{y} = \frac{e}{m} \left(-\frac{V_0}{d} \right) \left[\frac{\omega t_1^2}{2} + \delta t_1 \right] = -\frac{V_0}{d} \left[\frac{\omega l_1^2}{2v_0^2} + \frac{\delta l_1}{v_0} \right]$$

where v_0 , defined by $1/2 mv_0^2 = E$, is assumed to be unchanged during the passage of the ion between the plates. Then

$$y_1 = -\frac{V_0}{d} \left[\frac{\omega l_1^3}{6v_0^3} + \frac{\delta l_1^2}{2v_0^2} \right]$$

But $y_s = y_1 + y_2 = y_1 + \dot{y} \frac{l_2}{v_0}$

$$= \frac{e}{m} \left(-\frac{V_0}{d} \right) \left[\frac{\omega l_1^2}{2v_0^3} \left(\frac{l_1}{3} + l_2 \right) + \frac{\delta l_1}{2v_0^2} (l_1 + 2l_2) \right]$$

Differentiating,

$$\Delta y_s = \frac{1}{4} \ell_1 (\ell_1 + 2 \ell_2) \left(\frac{e V_0}{E d} \right) \Delta \delta$$

and since $\Delta \delta = \omega \Delta t_o$, $\Delta t_o = \frac{\Delta y_s}{w.s.}$

where w.s. = writing speed = $\frac{\omega e V_0 \ell_1 (\ell_1 + 2 \ell_2)}{4 E d}$

Although not predicted by the simplified theory, the two bursts per rf cycle form separate images on the target, as shown by the following argument. An ion can emerge from the plates with zero angular deviation only if it arrives at the center of the plates at rf phase 0 or π , so that it receives exactly equal but opposite radial impulses. Although the final radial velocity is zero in these cases, the final radial displacement is not. An ion which arrives at the center of the plates at zero phase, that is, during an "upsweep" is accelerated downwards before the center of the plates, and upwards after the center. The net displacement is therefore below axis during an "upsweep" and similarly above axis during a "downsweep". To first order, the displacement from the axis, δb , is given by

$$\delta b = \frac{V_o \omega \ell_1^3}{16 d E_o} \quad (\text{Tu 58})$$

where E is the ion beam energy in electron volts.

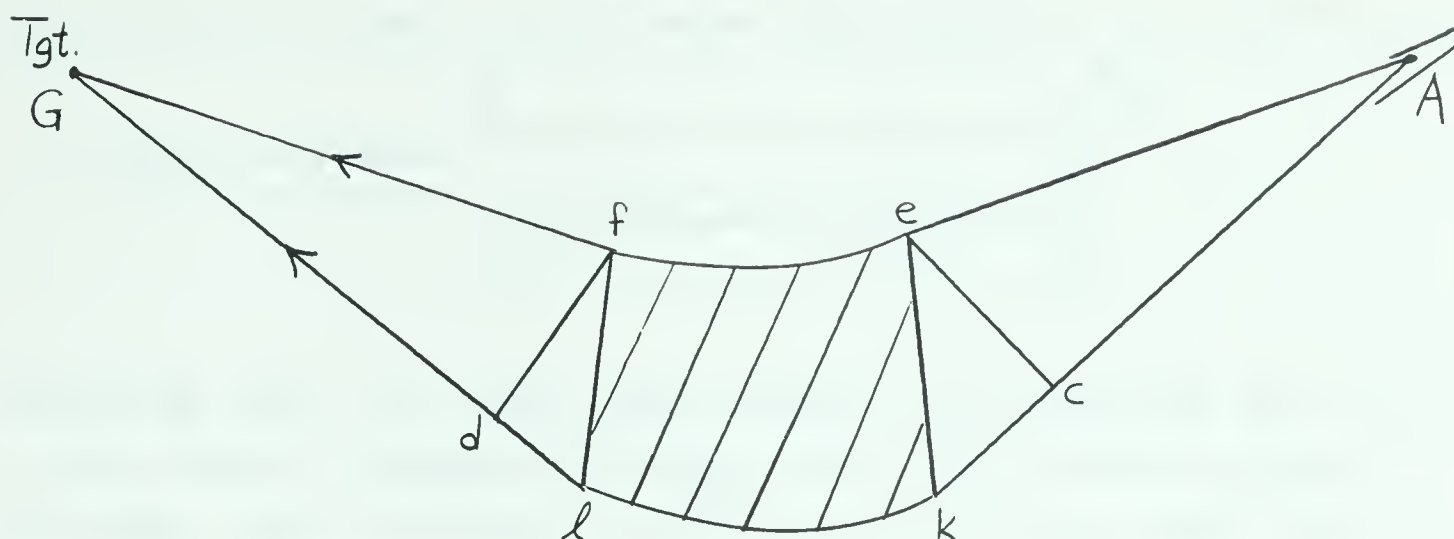
As mentioned in Chapter II, it is usually desirable to eliminate alternate sweeps. At the University of Alberta, this is achieved by means of a second set of plates, called alternate pulse eliminator plates, whose operation is described in Chapter II. "Refractor plates" (Tu 58) can also be used. A dc field is applied between the refractor plates to bring one sweep on-axis with respect to the other.

At the University of Alberta, deflector plate frequencies of 2.5 or 1.67 mc are commonly used, with deuterons in the energy range from 0.5 to 2.0 Mev. The burst duration is about 2 nsecs. At Brookhaven, Turner and Bloom (Tu 58) use deflector plates located at the exit end of the ion source, before the beam reaches the accelerator tube, to obtain a burst width on the target of about 4.5 nsecs. Such pre-acceleration pulsing reduces background, and makes possible the acceleration of larger beams by reducing markedly the average current through the accelerator tube. At Duke University, Lewis et al (Le 59) combined pre-acceleration and post-acceleration pulsing. Pre-acceleration bursts of from 5 to 10 nsecs were clipped to 1.2 nsecs duration by post-acceleration deflector plates.

To summarize, although pulsing by deflector plates is reasonably simple and effective, it is also very wasteful, since all of the beam between pulses, that is, about 99%, is discarded. To obtain a high burst intensity and a short burst length, a rather complicated pre-acceleration and post-acceleration deflection system is necessary, in conjunction with an ion source capable of high average currents.

(b) Beam Bunching

Bunching can be defined as changing the energy or path length of a burst of ions so that the trailing ions in a burst overtake the leading ions at the target. Two methods of bunching have been used. The Mobley magnet buncher (Mo 52) causes the leading ions in a burst to take a longer path to reach the target. The operation of the buncher is indicated by the diagram. The beam is swept across a field of the magnet M in the direction k to e by means of deflector plates at A in such a way that the path lengths from A to G become progressively shorter for later ions in a burst.

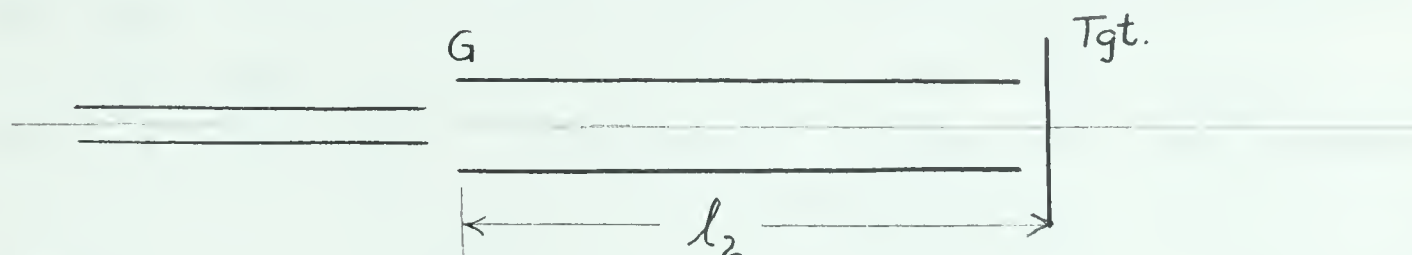


If v' = the velocity at which the ions are swept along ce , and if v = the ion velocity, then the sweep time $t_1 = ce/v'$. For bunching to occur, $t_1 = (ck + d)/v$, so that $v' = (ce/(ck + d))v$, and the length of the pulse on the target is $\Delta t = h/v'$, where h = the width of the beam.

The Mobley magnet buncher solves the problem of space-charge repulsion, and does not add appreciably to the energy spread of the beam. Disadvantages are the expense and bulk of the system, and the fact that a change in ion beam energy necessitates changes in at least sweep voltage and magnetic field intensity. A beam pulsing system has been developed by High Voltage Engineering Corporation which combines pre-acceleration beam deflection followed, after acceleration, by a Mobley compression magnet. The pulses generated in the terminal of the accelerator are of 1 ma intensity and 10 nsecs duration. The pulses are compressed by the Mobley magnet by a factor of 10 in time, giving 1 nsec pulses of 10 ma intensity at the target (Co 61).

The second method of bunching consists in speeding up the later ions in a particular burst so that they catch up with the earlier ions. This method of bunching, from its application in electron devices, is called klystron bunching. In its simplest form, klystron bunching consists of the super-position of a voltage of the form $V = V_b \sin \omega t$

to a burst of ions across some small gap in the drift tube.



Assuming that the ions pass through the bunching gap G in a time small compared with one cycle of the modulating voltage, the ion energy in l_2 for ions which pass G at time t_1 is given by

$$\frac{1}{2} m v^2 = e(V_0 + V_b \sin \omega t_1) \text{ where } eV_0 = \frac{1}{2} m v_0^2.$$

$$\text{Then } v = v_0 (1 + \alpha \sin \omega t_1)^{1/2}, \text{ with } \alpha = \frac{V_b}{V_0},$$

$$\text{and for } \alpha \ll 1, \quad v \approx v_0 (1 + \alpha/2 \sin \omega t_1).$$

Let t_2 be the time of arrival at the target of an ion which passed the buncher gap G at time t_1 . Then approximately

$$t_2 = t_1 + \frac{l_2}{v_0} (1 - \alpha/2 \sin \omega t_1)$$

$$\text{Differentiating, } dt_2 = dt_1 (1 - k \cos \omega t_1)$$

$$\text{where } k = \text{the bunching parameter} = (\omega \alpha l_2) / 2v_0.$$

$$dt_2 = 0 \text{ if } k = 1, \text{ assuming that } \cos \omega t_1 \approx 1.$$

The difficulty with klystron bunching is that bunching occurs over only a small part of the cycle of the modulating voltage, and so can only be used to compress already rather short bursts.

Klystron bunching of positive ion beams has been reported by several workers. Flerov and Tamonov (Fl 57) compressed 200 kev, 35 nsec bursts by as much as a factor

of 70. The steady beam from the ion source was 67 μ amp. The peak current corresponding to a bunching factor of 70 at an 18% duty cycle was about 5 ma. Huber et al (Hu 61) modulated the extraction voltage of a duo-plasmatron ion source by means of a 4 Mc/s HF-generator. The dc component of the extraction voltage was 30 kev. By suitable adjustment of the HF-amplitude, time focussing of alternate bursts on the target was achieved. Peak currents of 3 ma were obtained on the target with a width of 3 nsecs. Delaney (De 55) calculated that for simultaneous arrival of all protons which followed by time t the first proton in a burst, it is necessary to impress on the beam a modulation

$$\Delta V = V_0 \left[\frac{1}{\left(1 - \frac{t}{T_0}\right)^2} - 1 \right]$$

where V_0 and T_0 refer to the energy and flight time of unmodulated protons. He simulated the above modulating voltage to compress 5 kev, 200 μ amp, 380 nsec long bursts of protons. The theoretical bunching factor, neglecting space charge effects, was 16.5; the observed bunching factor was only 4.3. A calculation on the debunching effect of space charge gave a new theoretical bunching factor of 7.7 rather than 16.5. Schrader (Sc 58) attempted to produce short ion bursts by applying a sinusoidal bunching voltage to ions at the extractor of an rf ion source. However, a large signal was found to be imposed on the collector by the two radio-frequency voltages used in the system. The ion pulse appeared only as a superimposed blip on a 3-mc sinusoidal signal. Several methods were tried to reduce the interference of the rf signals with little success.

It should be mentioned that the beam quality, as measured by energy and/or angular spread, is necessarily diminished

in the process of burst production. A theory on the degradation of beam quality due to pulsing has been developed by Fowler and Good (Fo 60). If a steady "mono-energetic" beam is chopped by beam sweeping, then $\Delta E \Delta t = \Delta_{py} \Delta_y$ where ΔE is the energy that must be introduced into a monoenergetic beam in order to produce bursts as short as Δt . The y-component of momentum spread and the object size, after chopping, are respectively Δ_{py} and Δ_y . In klystron bunching of a nearly parallel pulsed beam, the relationship $\Delta E_a \Delta t_a = \Delta E_b \Delta t_b$ holds, relating the product $\Delta E \Delta t$ before bunching to that which exists after bunching.

(c) Plasma Pulsing

A third approach to beam pulsing consists in pulsing the ion source itself, that is, plasma pulsing. This approach should ideally be the most efficient with respect to beam wastage, and should cause less beam degradation than beam chopping or bunching. It has been found that an rf excited ion source produces a beam which is modulated to the order of 30% at the excitation frequency (Ph 58); it remains to be seen whether this modulation can be controlled and so utilized in the production of short ion bursts. In general, it is difficult to produce short ion bursts through plasma pulsing owing to the difficulty of controlling a plasma; further, it is possible for the required pulse duration to be comparable with the plasma formation time.

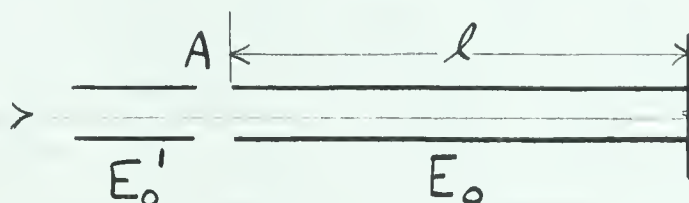
II. Mathematics of Bunching

In this work it was hoped to bunch an ion beam emerging from the extractor canal of an rf ion source, and by applying a suitable waveform, to bunch over a larger duty cycle than allowed by simple klystron bunching. Pre-acceleration

bunching had the advantage of allowing the modulating voltage to be of low amplitude.

The system consisted of a radio-frequency ion source* followed in succession by a "buncher tube", an accelerator tube, and a drift tube. Ideally, nearly all the bunching should occur in the buncher tube, after which the ions should be accelerated as rapidly as possible to reduce subsequent space-charge effects. Modulation waveforms for perfect bunching are derived below.

For the simple case of bunching across a single gap, the unmodulated ion energies at $t = 0$ are given by E_0' and E_0 , where $E_0 = E_0' + V_0$. Then $T_0 = (\sqrt{\frac{m}{2}} \ell) / \sqrt{E_0}$



For $t > 0$, a modulation ΔE is applied, so that the new ion energy in ℓ becomes $E_0 + \Delta E$. The "bunching criterion" is then defined by

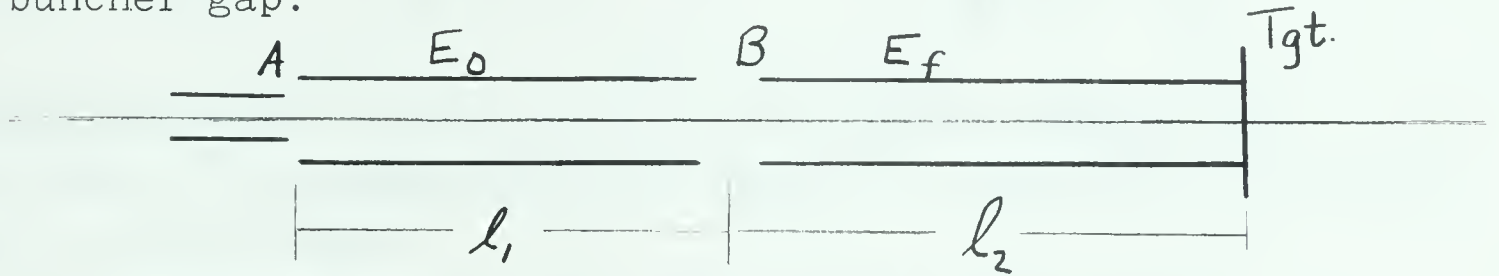
$$T_0 - t = \frac{\sqrt{\frac{m}{2}} \ell}{\sqrt{E_0 + \Delta E}}$$

from which $\left(1 - \frac{t}{T_0}\right) = \sqrt{\frac{E_0}{E_0 + \Delta E}} \text{ --- 1}$

or $\Delta E = E_0 \left[\frac{1}{\left(1 - \frac{t}{T_0}\right)^2} - 1 \right] \text{ --- 2}$

*Supplied by High Voltage Engineering Corporation, Burlington, Massachusetts.

A wave form can therefore be generated which, applied across a gap A, should bunch all ions reaching the gap. It has been assumed that negligible time is spent crossing the buncher gap.



Suppose there exists a drift tube, held at a fixed potential, after the buncher tube. The ion energy in the drift tube at $t = 0$ is then given by E_f . The ion energy in the drift tube for $t > 0$ depends on the phase of the modulating voltage when the ions reach point B in the above diagram. If nearly all of the bunching occurs in the buncher tube, then all of the ions in a given pulse pass point B at approximately the same phase of the modulating voltage. Two conditions will be considered; (i) the bunch reaches point B at phase 0, that is, at $\Delta E = 0$, and (ii) the bunch reaches B when $\Delta E = \Delta E_{\max}$. In this case ion energy in l_2 is $E_f + \Delta E - \Delta E_{\max} = E_f^* + \Delta E$.

For case (i) the transit time for a particle entering l_1 at $t = 0$ is

$$T_0 = T_{01} + T_{02} = \frac{kl_1}{\sqrt{E_0}} + \frac{kl_2}{\sqrt{E_f}}$$

Application of the "bunching criterion" gives

$$T_0 - t = \frac{kl_1}{\sqrt{E_0 + \Delta E}} + \frac{kl_2}{\sqrt{E_f + \Delta E}}$$

which reduces to

$$\left(1 - \frac{t}{T_0}\right) = \frac{T_{01}}{T_0} \sqrt{\frac{E_0}{E + \Delta E}} + \frac{T_{02}}{T_0} \sqrt{\frac{E_f}{E + \Delta E}}$$

For condition (ii), the expression is

$$\left(1 - \frac{t}{T_0^*}\right) = \frac{T_{01}}{T_0^*} \sqrt{\frac{E_0}{E_0 + \Delta E}} + \frac{T_{02}^*}{T_0^*} \sqrt{\frac{E_f^*}{E_f^* + \Delta E}}$$

where, in order to solve for t , both ΔE and $\Delta E_{\max}$ must be known. The expressions can easily be extended to include more tube sections.

Now suppose that the ions are undergoing uniform acceleration in the buncher tube. If the length is l_1 , then the average ion velocity is given by $\bar{v} = v_0 + 1/2 a l_1 / \bar{v} = v_0/2 + 1/2 \sqrt{v_0^2 + 2al_1}$. Define $E_a = 1/2 m \bar{v}^2$. Then if the initial and final ion energies are E_{f0} and E_f , the equation for $\bar{v}$ becomes

$$E_a = 1/4 \left[E_{f0} + E_f + m a l_1 + m v_0 \sqrt{v_0^2 + 2a l_1} \right]$$

$$a = \frac{E_f - E_{f0}}{m l_1}$$

$$\text{so that } E_a = 1/4 \left[E_f + E_{f0} + 2\sqrt{E_f E_{f0}} \right]$$

Then for $t > 0$, the "bunching criterion" gives

$$T_0 - t = \frac{\sqrt{m/2} l_1}{\sqrt{E_a + \delta E}}$$

where δE is defined by

$$E_a + \delta E = 1/4 \left[(E_{f0} + \Delta E) + (E_f + \Delta E) + 2\sqrt{(E_{f0} + \Delta E)(E_f + \Delta E)} \right]$$

from which

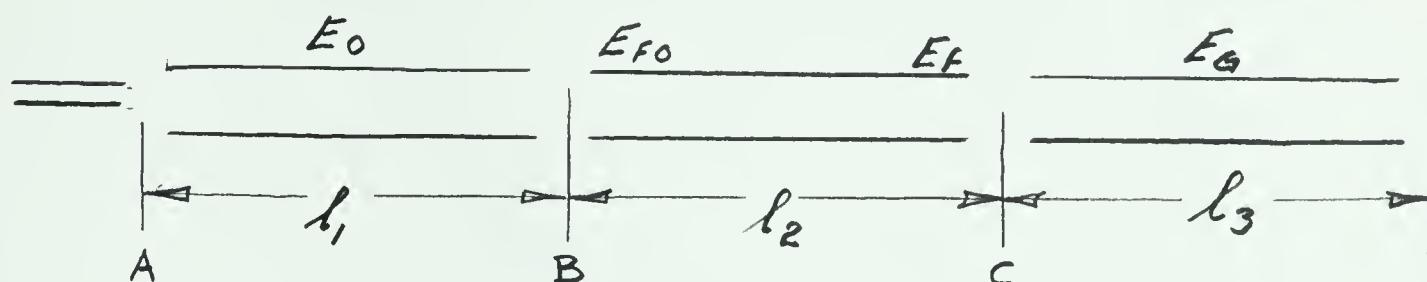
$$\delta E = 1/2 \left[\Delta E + \sqrt{E_f E_{f0}} (X - 1) \right]$$

where

$$X = \sqrt{\left(1 + \frac{\Delta E}{E_{f0}}\right)\left(1 + \frac{\Delta E}{E_f}\right)}$$

$$\text{Then, as before } \left(1 - \frac{t}{T_0}\right) = \sqrt{\frac{E_a}{E_a + \delta E}}$$

For a system consisting of a buncher tube, an accelerator tube, and a drift tube, as indicated below, the equation for



"perfect bunching" can be written for condition (i) as

$$(1 - \tau/T_0) = \frac{T_{01}}{T_0} \sqrt{\frac{E_0}{E_0 + \Delta E}} + \frac{T_{02}}{T_0} \sqrt{\frac{E_a}{E_a + \delta E}} + \frac{T_{03}}{T_0} \sqrt{\frac{E_G}{E_G + \Delta E}}$$

where E_a , δE , and κ are as defined in the preceeding paragraph. For condition (ii) ($\Delta E = \Delta E_{\max}$ as the bunch passes point B) the form of the equation is unchanged, but the quantities E_G , E_f , and E_{f0} (and consequently T_0 , E_a , δE , and κ) have the new values given by subtraction of $\Delta E_{\max}$, as has been previously indicated.

Figure 6-1 shows sample curves generated from the above equations for a system consisting of a buncher tube, an accelerator tube, and a drift tube. For all curves, $l_1 = 20$ cm and $E_{f0} = 11$ kev. Condition (ii) has been used in obtaining curve 4; condition (i) ($\Delta E = 0$ as the bunch passes point B) has been used for all other curves. Other values used are tabulated below.

Curve No.	E_0 (kev)	$E_f = E_G$ (kev)	$l_2 = l_3$
1	2	-	0
2	2	150	2m
3	2	100	2m
4	2	100	2m
5	1.5	-	0
6	1.5	150	2m
7	1.5	100	2m

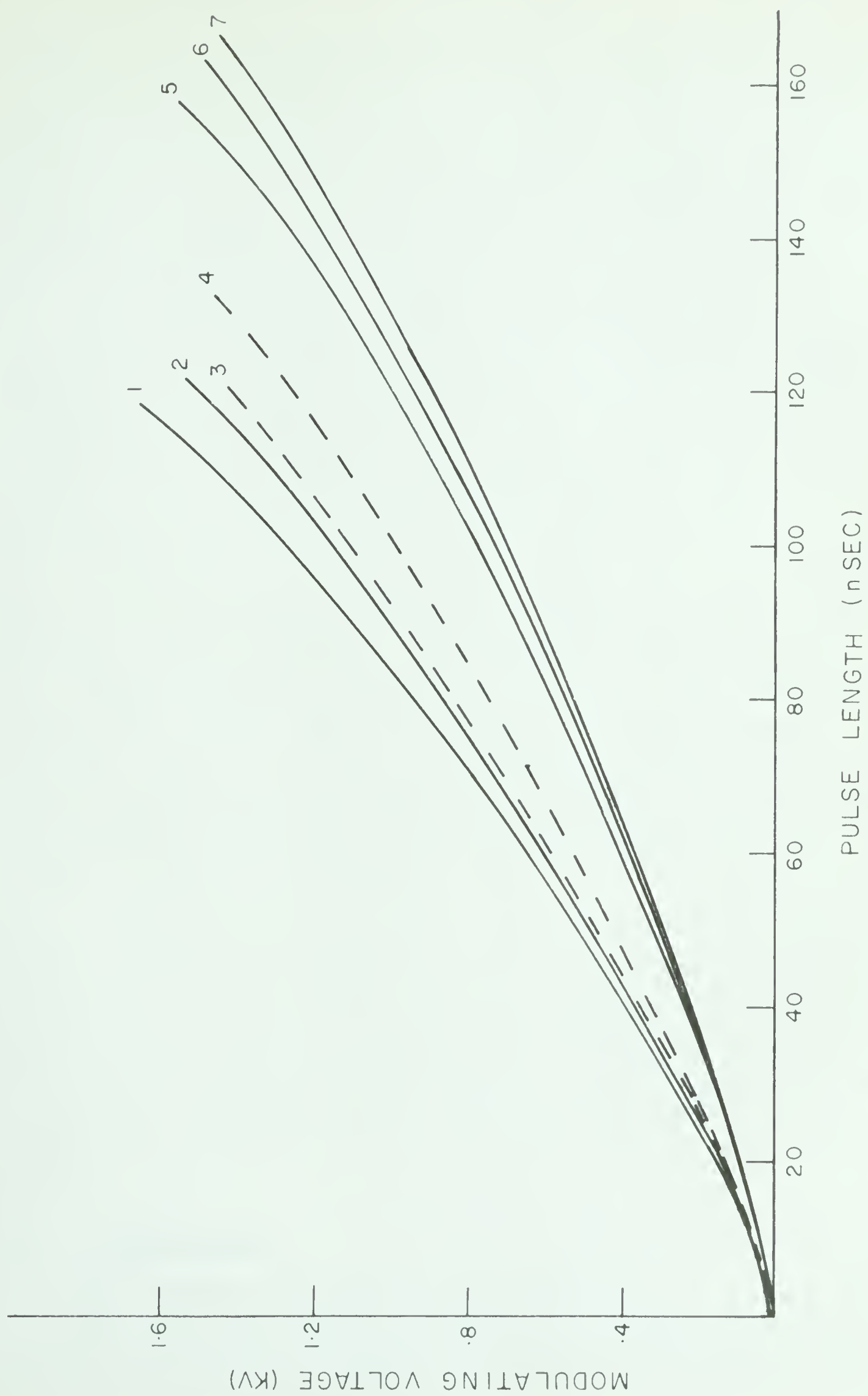


Figure -1 Modulation voltage wave-forms for "perfect" bunching.

Curves 1 and 5 show that nearly all of the bunching does occur in the "buncher" tube. The rather large difference between curves 3 and 4 shows the effect of the phase of the modulating voltage at the instant when the bunch leaves the buncher tube. The value of E_G , indicated by the difference between curves 2 and 3 (and between curves 6 and 7) has little effect on the pulse length.

The idealized wave forms can be reasonably well approximated by a suitable portion of a sinusoidal wave-form, as is indicated by Figure 6-2. Curve 1 represents a "perfect" bunching curve for a single buncher tube of length 60 cm. $E_0 = 15$ kev, for which $T_0 = 500$ nsec. The equation of the curve is $\Delta E' = (1 - t')^{-2} - 1$ with $\Delta E' = \Delta E/E_0$ and $t' = t/T_0$. Curve 2 is a plot of the equation $\Delta E' = 1.129 - 1.296 \cos \left[(180t')^\circ + 29^\circ 24' \right]$ which is the equation used by Delaney. The modulating frequency is 1 Mc, corresponding to a period of 100 nsec. The bunching curve only extends over 30° of the modulating voltage. However, the fit to curve 1 is reasonably good, since it gives a theoretical bunching factor greater than 20. The peak-to-peak amplitude of the modulating wave-form is 38 kv. Curve 3 is a plot of $\Delta E' = .433 \left[\sin (360t' - 30)^\circ + .5 \right]$. The bunching factor is 17, so that the fit to curve 1 is not quite as good as it was for curve 2. The modulating frequency is, however, 2 Mc, so that the curve extends for 60° of the modulating wave-form. The peak-to-peak amplitude is 13 kv, which is a much more reasonable value than the 38 kv required for curve 2.

III. Experimental

(a) General Experimental arrangement

The first experimental arrangement used consisted of a radio-frequency ion source, followed in succession by a

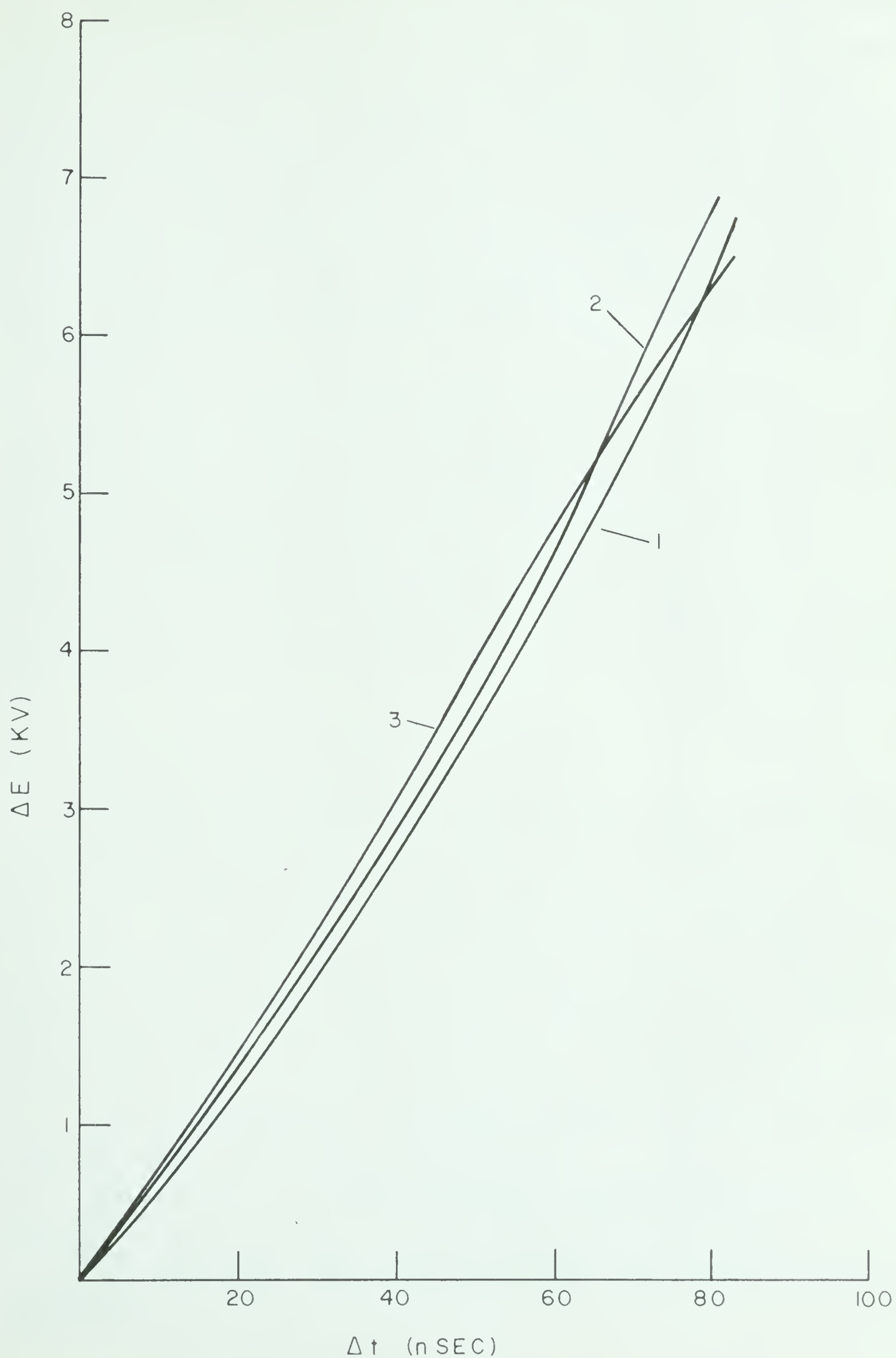


Figure 6-2 Approximations to a "perfect" bunching wave-form.

"buncher" tube, an accelerator tube, and a drift tube. For convenience the ion source was held near ground potential, and the drift tube and the target were floated at a high negative potential which was supplied by a 150 kv high tension set.* This arrangement allowed the ion source and any modulating supplies to be held near ground potential. However, it did make the detection of ion bursts at the target more difficult than when the target is held at ground potential. The curves shown in Figure 6-1 were calculated for the geometry used in this experimental arrangement.

The experimental system was later simplified by replacing the 2 meter long accelerator tube and the drift tube by a short (25 cm) drift tube. In this system, the negative acceleration voltage of up to 60 kv ** was applied between the buncher tube and the drift tube. Again the ion source was kept at ground potential. The general form of this arrangement is as indicated in Figure 6-7.

(b) Ion Source Characteristics

It was first necessary to determine the energy and homogeneity of the ion beam from the ion source. The rf ion source *** was of the type described by Moak et al (Mo 51). The ions are focussed through an extractor canal at the cathode by means of a voltage applied to the anode, which is also called the probe. A silica sleeve immediately above the extractor canal acts as a virtual anode.

*Model 6005/150-2, Sorensen and Co., Inc., High Voltage Systems Lab., New York 29, New York.

**Model 60 PN, regulated high voltage power supply, Spellman High Voltage Co., New York 67, New York.

***Provided by High Voltage Engineering Corporation as standard equipment with the type AK, 2 Mev Van de Graaff generator.

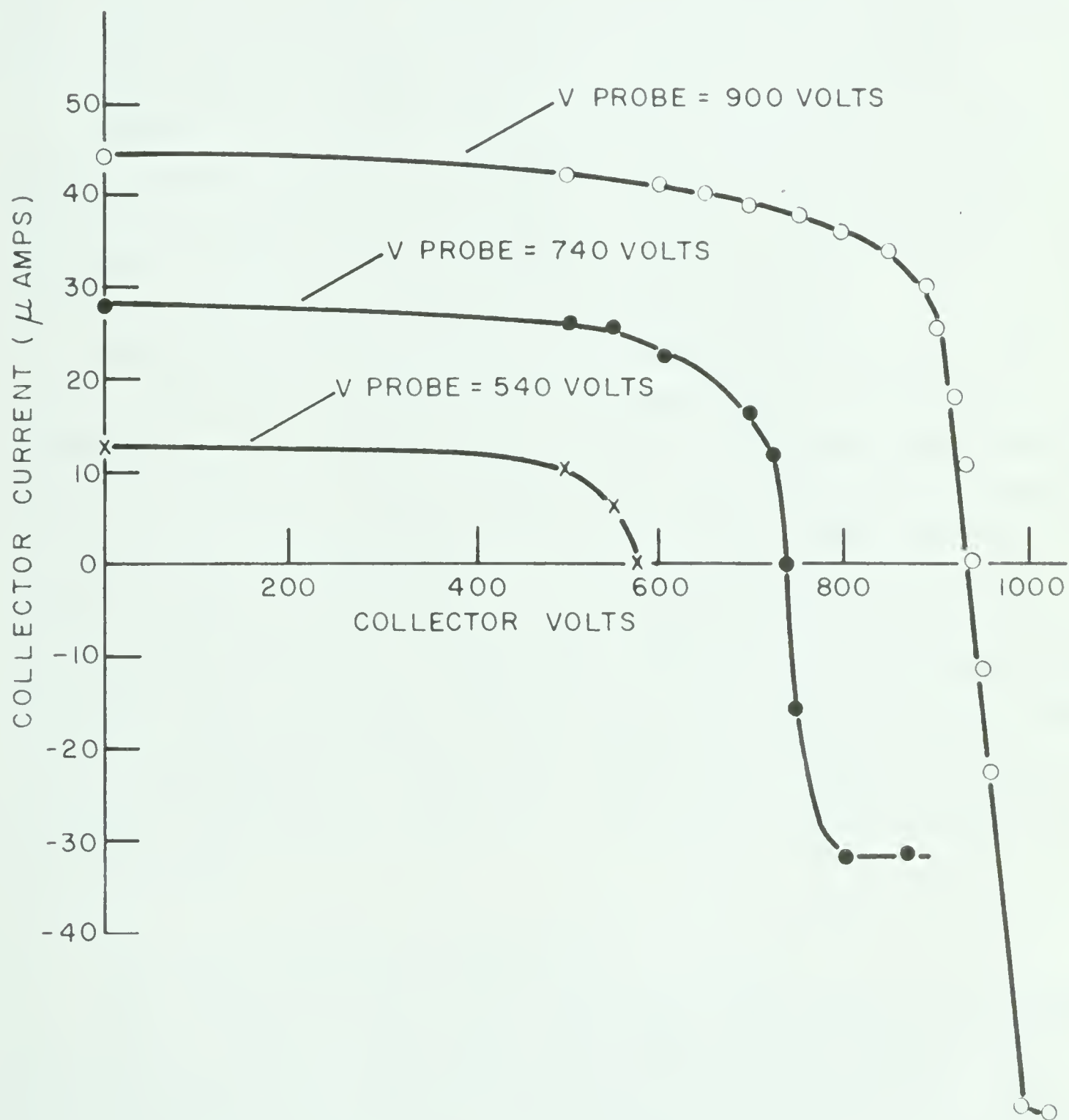


Figure 6-3 Measurement of ion source beam homogeneity.

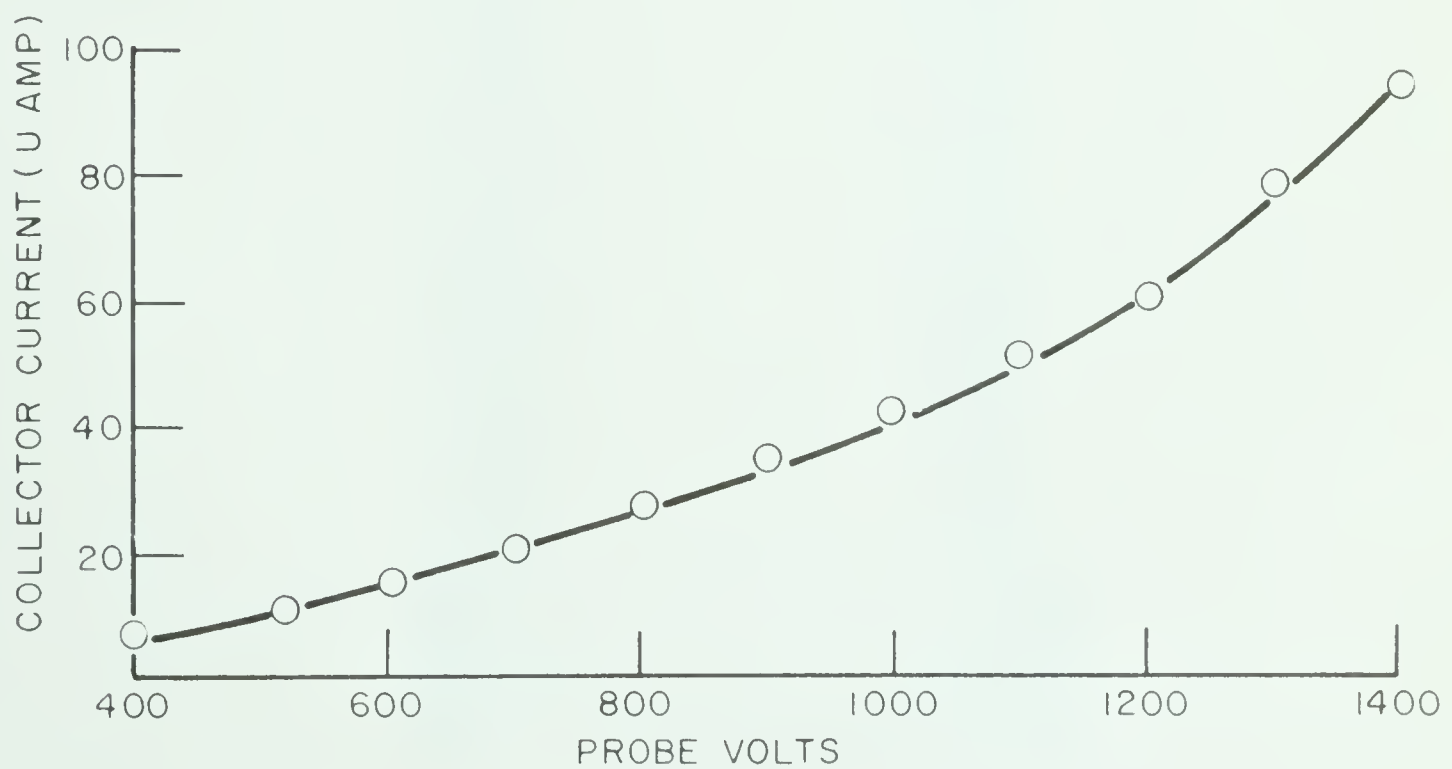
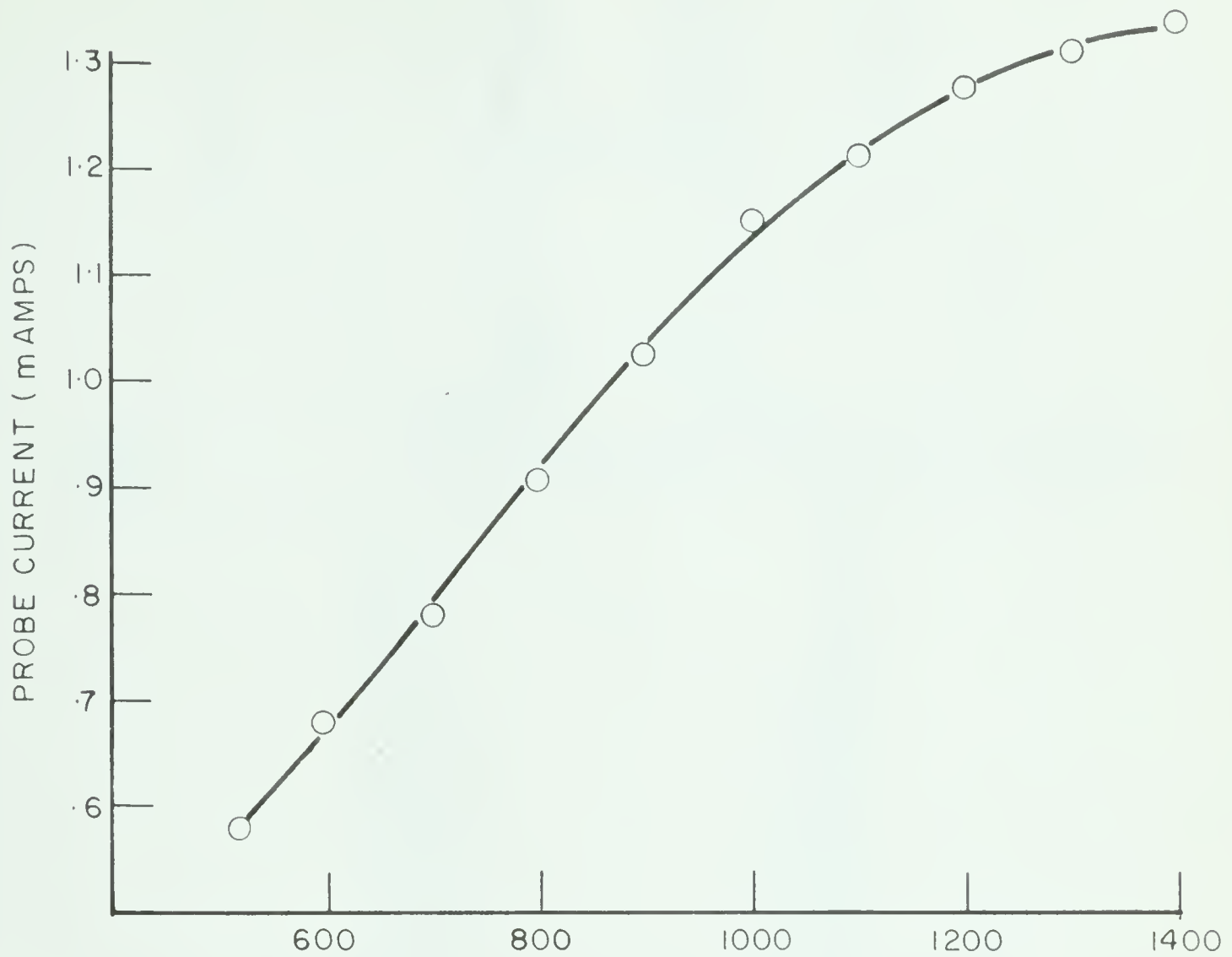
An ion collector was positioned some 2 inches from the ion source aperture, and measurements were made of collector current as a function of collector voltage. The data, shown plotted in Figure 6-3, show that the ion energy is approximately that given by the probe voltage; most of the ions do not have an energy spread greater than ± 20 ev. The negative current readings for collector voltages greater than the probe voltage is due to electron collection.

Figure 6-4 shows plots of collector current, and of probe current, that is, anode to cathode plasma current, plotted as a function of probe voltage. Up to a probe voltage of 1400 volts, the output of the source is a smoothly increasing function of probe voltage.

Measurements were also made of the impedance of the probe, in order to check on the feasibility of directly pulsing the ion source probe. The dc impedance was approximately 1 Megohm. The ac impedance was measured by means of a sine wave generator whose output was taken through a known load to the probe. Between 200 kc and 5 Mc, the source impedance was found to be capacitative, and of approximately 27 pf in magnitude. That is, at a frequency of 1 Mc, the reactance of the source is about 6 kohms. The source impedance is therefore sufficiently high to make feasible bunching by means of a suitable wave-form applied to the probe.

(c) Ion Detection Apparatus

For observing the beam visually, the ions were allowed to strike a metal disc which had been thinly coated with zinc sulphide, and then covered with a fine metallic mesh to conduct the charge from the surface of the zinc sulphide. No difficulty was experienced in observing the beam spot on the target for ion energies as low as 15 kev. For detection of ion pulses, the arrangement shown in Figure 6-5 was used. The ions were allowed to strike a thin NE 102



ION SOURCE CHARACTERISTICS

Figure 6-4 Ion source characteristics

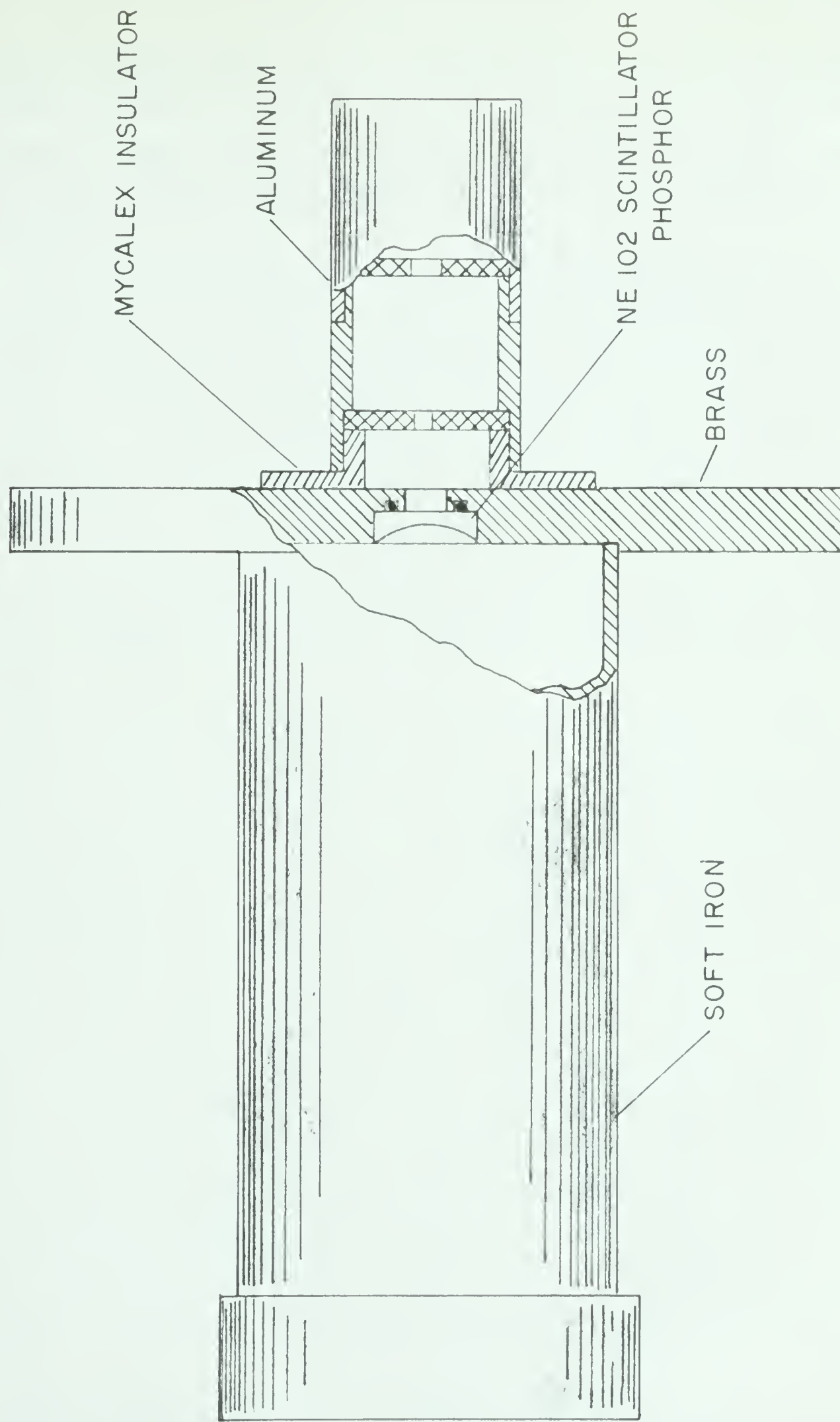


Figure 5-5 System used for the detection of ion bursts

phosphor, which was used in conjunction with an RCA 6810 photomultiplier. The face of the phosphor was aluminized to reduce light absorption, and was further shielded against light and electron bombardment by a 1/8 inch diameter collimator.

The circuitry employed is shown in Figure 6-6. It was necessary to "float" the photomultiplier and dynode bleeder chain at the target voltage; that is, up to nearly -40 kv. Values of the dynode resistors were chosen so that a current of 0.91 ma through the dynode bleeder chain corresponded to a photocathode to anode potential difference of 2000 volts. For each different value of target voltage used, the value of R_1 in Figure 6-6 was adjusted to maintain the current output of the Spellman power supply (and so the current through the dynode resistor chain) at approximately 0.9 ma.

Due to the increased ion energy, the pulse height observed on the oscilloscope screen increased with increasing values of target voltage. With a very thin aluminum layer on the phosphor, pulses were observed on the oscilloscope at ion energies as low as 10 kev, but a better signal-to-noise ratio was obtained for energies of about 30 kev. Difficulties in the detection system were caused by electrical breakdowns, light leaks into the phosphor, mainly from the luminous ion source plasma, and by rf pick-up from the ion source (80 Mc) and from the high-voltage power supply (about 100 kc). A serious limitation was caused by the fact that to reduce noise it was necessary for the average ion current striking the NE 102 to be no larger than a small fraction of a μ amp. The corresponding average anode current in the photomultiplier tube was kept below 50 μ amp.

(d) Methods of Ion Pulsing Attempted

It was initially hoped to bunch the ions at the ion source extraction energy of approximately 1 kev. It was

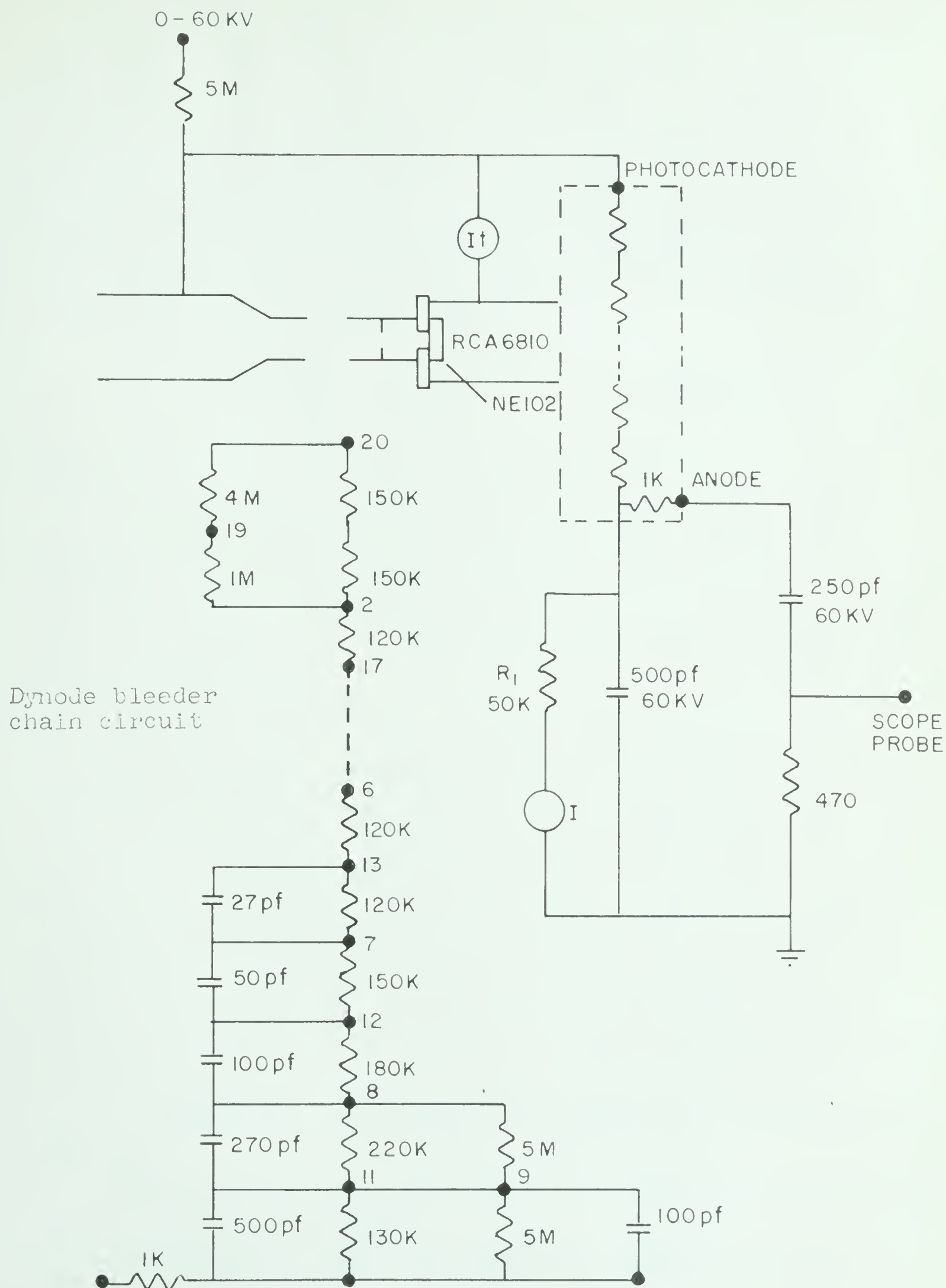


Figure 6-6 Photomultiplier circuitry used in the detection of ion bursts.

found, however, that the transmission of ion current through the 20 cm long, 5/8 inch diameter, beam-buncher tube was low unless the ion energy was increased to several kev. A method of ray-tracing was used to determine the paths followed for several different starting ion trajectories. "Resistance paper"* with the appropriate electrode shapes marked with silver conducting paint, was used to determine the equipotential lines, after which the ray-tracing was carried out using Snell's law;

$$\frac{\sin \theta_1}{\sin \theta_2} = \left(\frac{v_2}{v_1} \right)^{1/2} \quad (\text{Co } 50)$$

The ray tracing indicated that at ion energies of less than several kev, a low buncher tube transmission could be expected. Further, variations in flight paths due to different ion trajectories through the system were sufficient to cause serious time dispersions at low ion energies. It was consequently decided to abandon the idea of bunching at a low ion energy.

A system was devised, however, for "chopping" rather than bunching the ion beam by means of two brass "grids" mounted at the exit of the ion source extraction canal. The grid arrangement used is shown in Figure 6-7. A positive dc bias was used to prevent ion current flow through the grids except when negative square-wave pulses were applied. The grid pulses, of approximately 120 volts amplitude and of lengths down to 26 nsecs, were obtained from a pulse generator** followed by two wide-band amplifiers***.

*"Teledeltos" facsimilie recording paper, supplied by Western Union Telegraph Company, 60 Hudson St., New York 13, New York.

**Model 120 B pulse generator, E-H Research Laboratories, Inc., Oakland, California.

***Model 460 B wide-band amplifier, Hewlett Packard, Palo Alto, California.

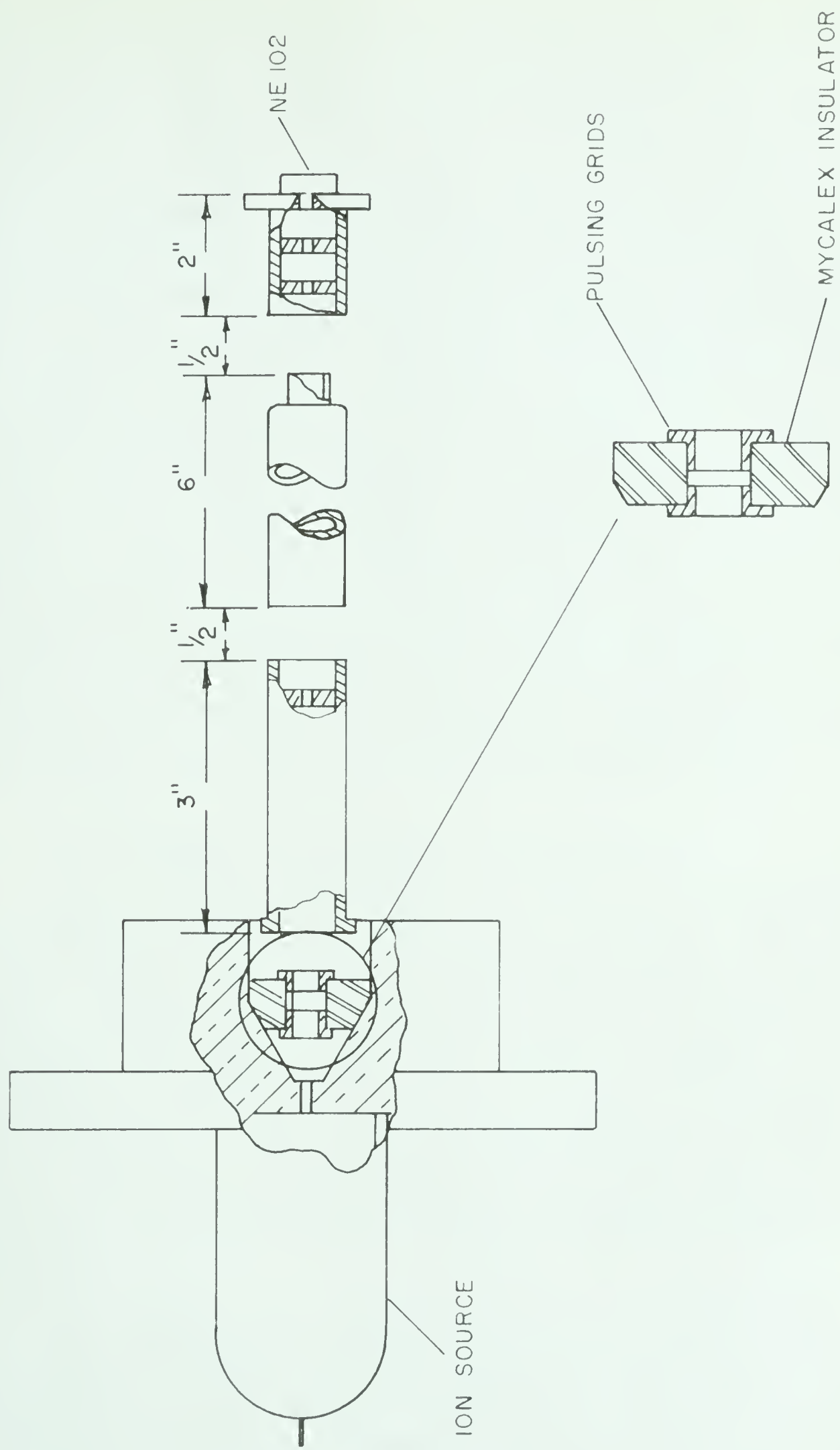


Figure 6-7 The "Grid" ion-pulsing arrangement

Typical grid pulses and the resulting observed oscilloscope wave-forms (shown without accompanying noise pulses), are given in Figure 6-8. The oscilloscope sweep was triggered by means of the input grid pulses. For short input grid pulses, two output pulses were obtained for each input grid pulse. Rough calculations showed that the pulse delay times were appropriate for mass 1 and mass 2 beam bursts on the phosphor. Further, the relative size of the two pulses was found to vary with the conditions of source operation, as expected if the two pulses were caused by mass 1 and mass 2 ion bursts. For longer input grid pulses (indicated by Figure 6-8(b)) only one output pulse was seen, of length about equal to that of the input pulse. The minimum output pulse length observed was about 50 nsec. No significant change in output pulse length was observed as the input pulse length was decreased from 60 to 26 nsec. Probably the system is not capable of producing shorter ion bursts, and so is of little practical value.

(e) Design of a Deflector Plate System

It is usually desirable to "chop" a dc beam before attempting to bunch it, and since a simple rf deflector plate system was apparently the most efficient means of beam chopping, a pre-acceleration deflector system was designed and constructed. An assembly drawing of the deflector plate system is shown in Figure 6-9. The system was designed to fit either the experimental test arrangements described in this chapter, or to fit directly into the high voltage terminal of the 2 Mev Van de Graaff generator.

The length and separation of the polished brass deflector plates are 2 inches and $3/4$ inches respectively; the plate separation can be adjusted by means of threaded teflon supports. A $1/8$ inch diameter beam defining aperture is located $1-1/2$ inches from the end of the deflector plates.

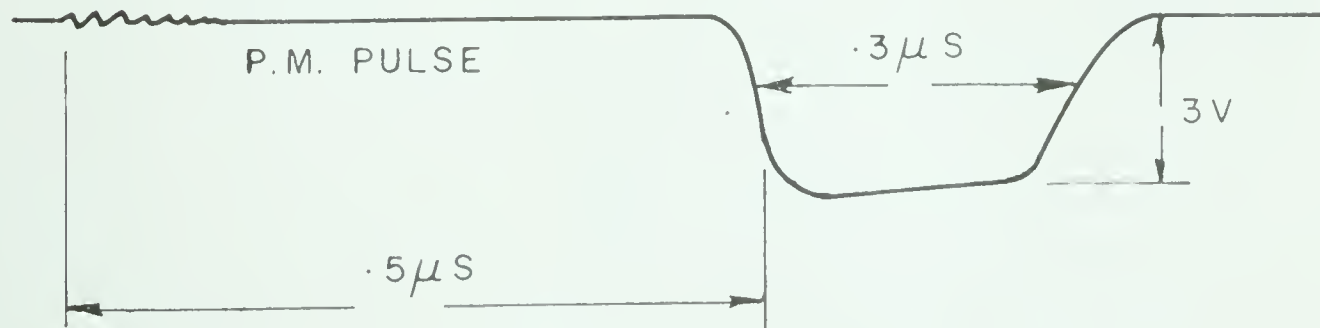
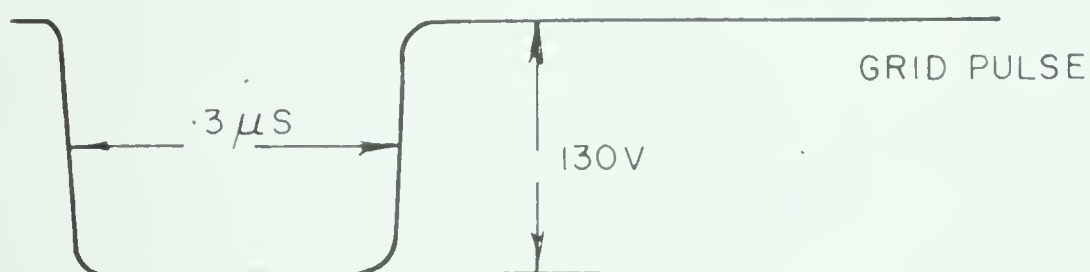
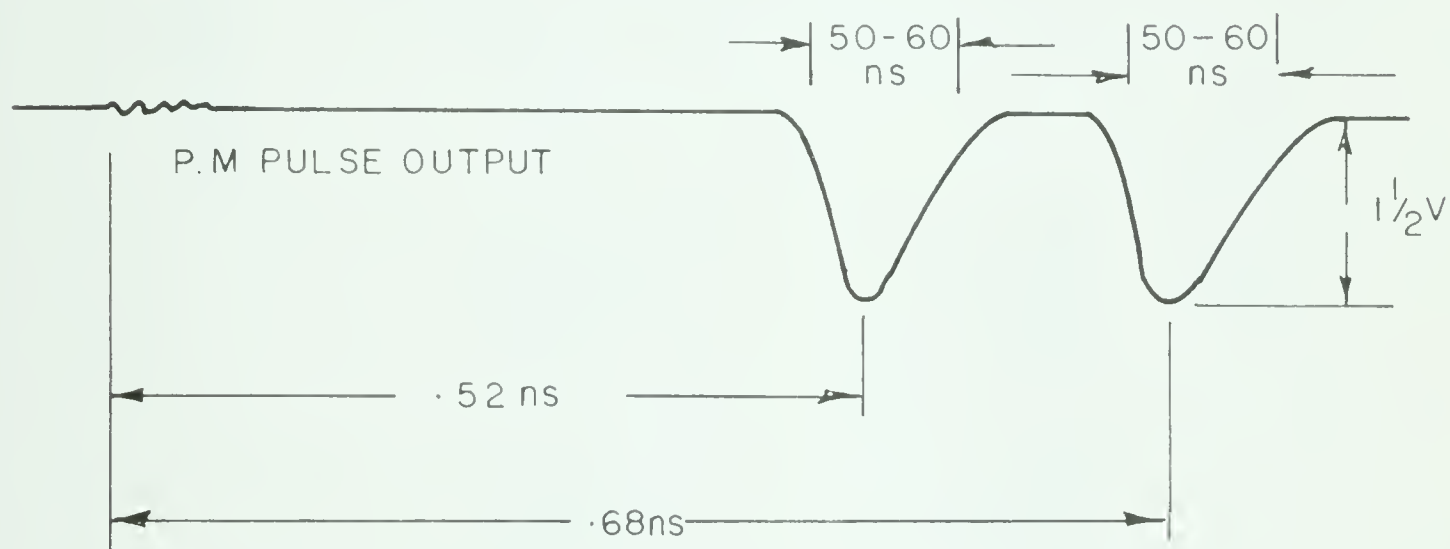


Figure 6-8 Typical wave-forms obtained using the grid pulsing arrangement.

$$V_{\text{probe}} = 700 \text{ V}, \quad V_{\text{bias}} = 760 \text{ V}, \quad V_{\text{HT}} = 30 \text{ kV}$$

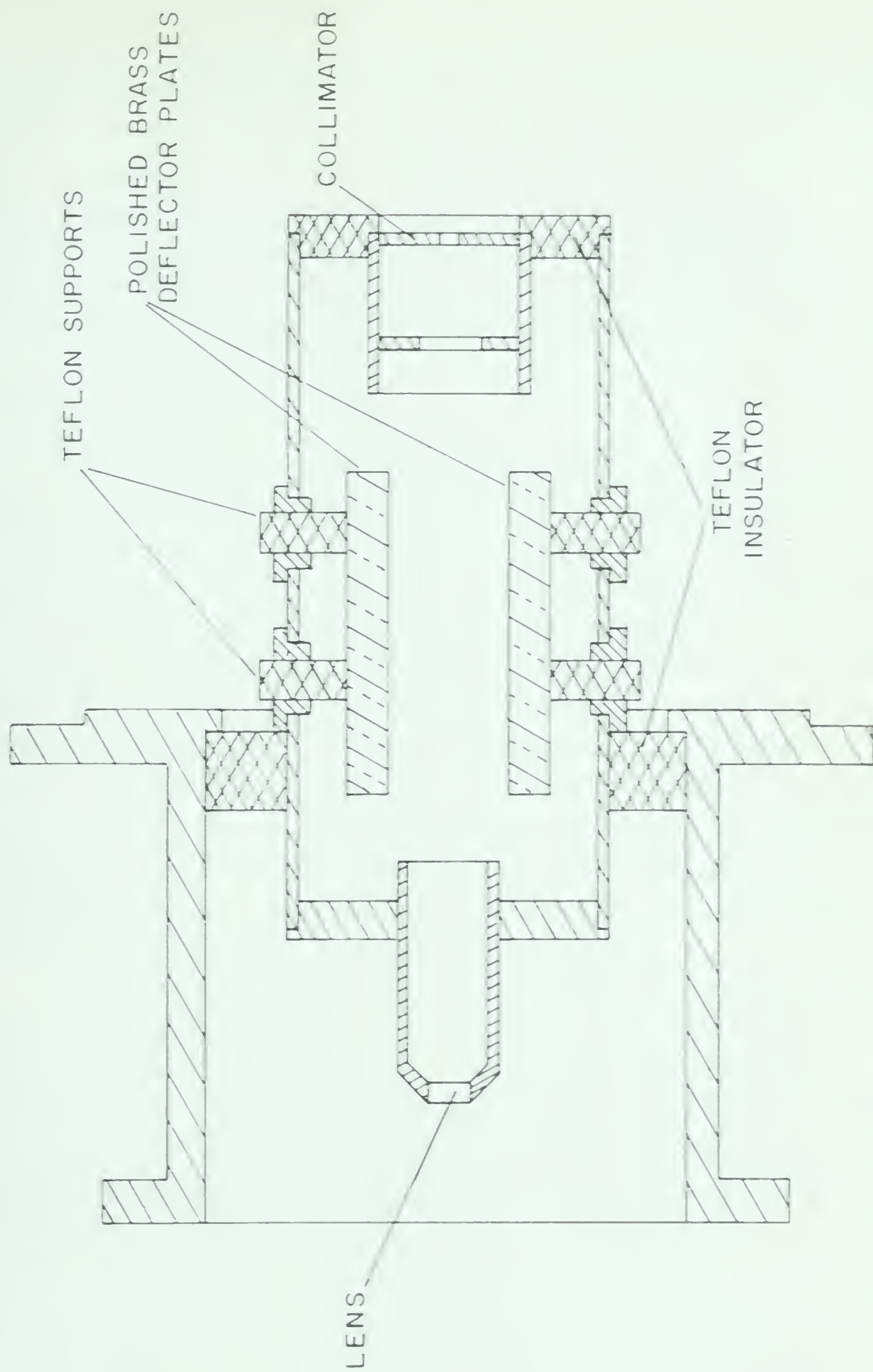


Figure 109. Assembly of the polished brass deflector plates.

Using the equations given by Turner and Bloom (Tu 58), the burst duration for 4 kev protons, assuming a 2000 volt peak-to-peak, 2.5 Mc rf voltage, is 6 nsec. However, under these conditions nearly one-half of the beam would be sufficiently deflected to strike the end of the brass deflector plates. Tests were not carried out using the deflector plates, as time was not available.

IV. Conclusions

The results of this work were disappointing, since they indicated that pre-acceleration ion-bunching should be carried out at an ion energy of at least several kev. Variations in flight time due to differing ion trajectories cause serious time dispersions at low energies. Ion focussing problems are themselves more serious at low energy. Apart from these difficulties, space charge repulsion may prevent successful low energy beam-bunching. Probably simple klystron bunching of a previously chopped, reasonably high-energy beam is the most practical method of bunching. Bunching over a larger duty cycle may be realized by approximating an ideal bunching wave-form by a suitable portion of a sinusoidal modulating voltage.

A method of pulsing an rf ion source by means of a grid arrangement located immediately after the extractor canal has been investigated. Such a pulsing system is feasible, but is probably of little practical value, since a square-wave grid pulse is required, and since the resulting target pulses are inferior to those attainable by means of deflector plate "beam chopping".

APPENDIX I

Calculation of Neutron Energies for the Reactions $B^{10}(d,n)C^{11}$ and $F^{19}(d,n)Ne^{20}$

Neutron energies in the laboratory system have been calculated for neutrons leading to the 6.48 Mev level in C^{11} at a deuteron energy of 1.91 Mev. Laboratory system neutron energies for neutrons leading to the ground state of Ne^{20} and to states at excitations of 1.63, 4.25, 4.97, 5.64, 6.17, 6.75, 9.34, 9.97, and 10.61 Mev have been calculated for deuteron energies of 1.50 and 2.00 Mev.

The energies for neutrons leading to the 6.48 Mev state in C^{11} have been calculated using the non-relativistic equation given by Marion and Allen (Ma 55)

$$E_3 = E_1 \frac{M_1 M_3}{(M_3 + M_4)^2} \left\{ 2 \cos^2 \theta + \frac{M_4(M_3 + M_4)}{M_1 M_3} \left[\frac{Q}{E_1} + 1 - \frac{M_1}{M_4} \right] \right. \\ \left. \pm 2 \cos \theta \sqrt{\cos^2 \theta + \frac{M_4(M_3 + M_4)}{M_1 M_3} \left[\frac{Q}{E_1} + 1 - \frac{M_1}{M_4} \right]} \right\}$$

The values were as follows:

$$M_1 = M_d = 2.014741 \text{ amu}$$

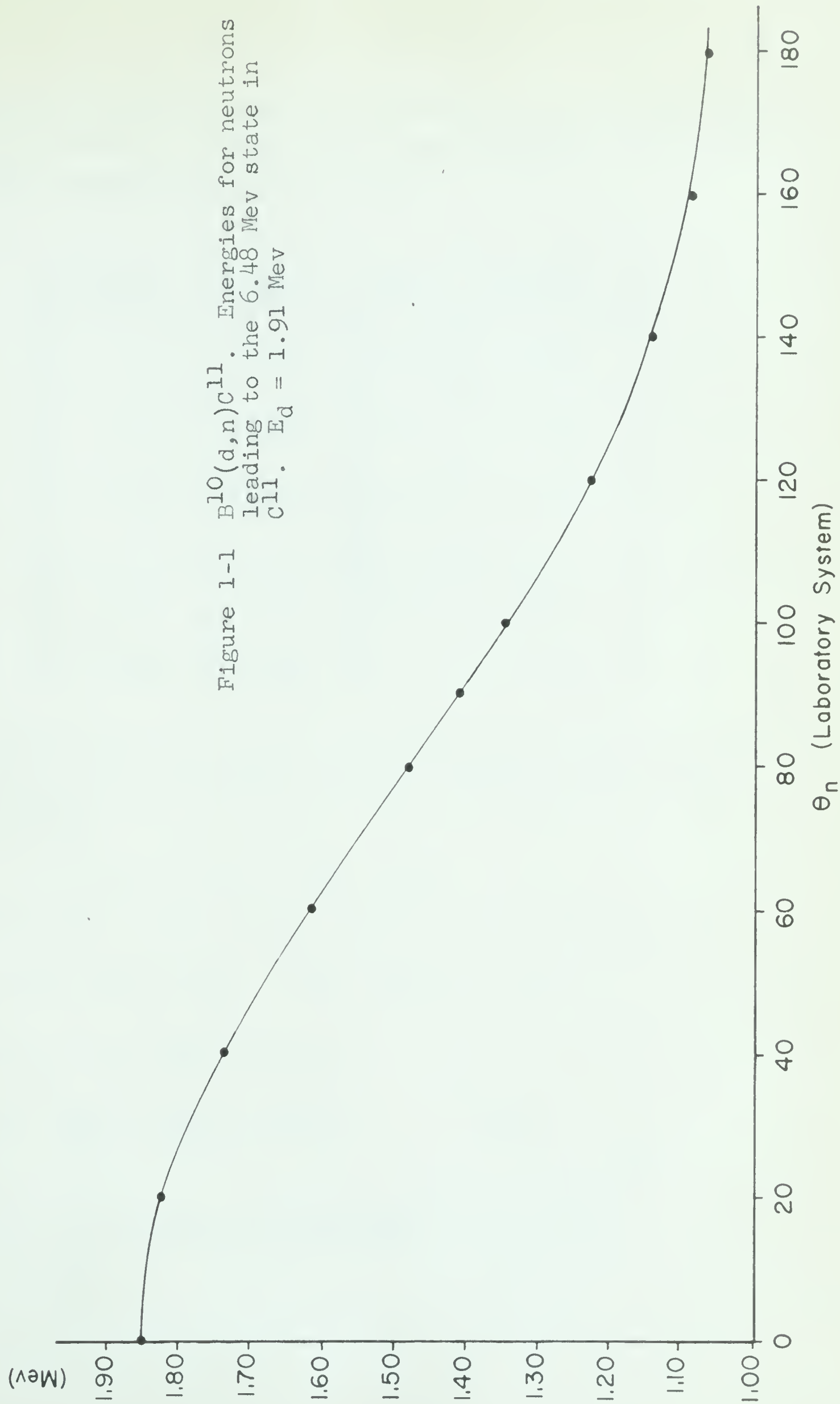
$$M_2 = M_B = 10.016110 \text{ amu}$$

$$M_3 = M_n = 1.008987 \text{ amu}$$

$$M_4 = M_C = 11.01495 \text{ amu}$$

$$Q = -0.024 \text{ Mev}$$

$$E_1 = 1.91 \text{ Mev}$$



The minus sign in the equation has been used for values of θ greater than 90° . Values of $E_3 =$ are tabulated below, and are shown graphically in Figure 1-1.

θ_{nlab}	$E_n(\text{Mev})$	θ_{nlab}	$E_n(\text{Mev})$
0°	1.854	100°	1.347
20°	1.823	120°	1.226
40°	1.739	140°	1.140
60°	1.616	160°	1.087
80°	1.482	180°	1.069
90°	1.408		

Neutron energies in the laboratory system for neutrons leading to states of Ne^{20} have been calculated using the relationship

$$E_n = A^2 + B^2 + 2AB \cos \phi$$

where ϕ is the center of mass angle for the neutron, and

$$A^2 = 1/2 m_n V_{cm}^2, \quad B^2 = 1/2 m_n v_n^2 \text{ cm}^2.$$

$$V_{cm} = \left(\frac{m_d}{m_i + m_d} \right) v_d \text{ lab}$$

Then $A = \frac{m_n}{m_d} \left(\frac{m_d}{m_i + m_d} \right) \sqrt{E_d}$, and

$$B = \left\{ \left(\frac{m_3}{m_n + m_3} \right) \left[\left(\frac{m_i}{m_i + m_d} \right) E_d + Q \right] \right\}^{1/2}$$

where m_1 is the mass of the target nucleus = 19.004 amu, and m_3 is the mass of the residual nucleus = 19.999 amu.

Then $A = 0.0673 \sqrt{E_d}$, and

$$B = 0.9758 \sqrt{.9047 E_d + Q}$$

Q for the ground state was taken to be 10.646 Mev. Tables of Marion and Ginzburg (Ma 54) were used for the transformation of the center of mass angle to laboratory angle. The variable x in the tables was evaluated to be

$$x = \sqrt{\frac{.00526}{1+1.105Q/E_d}}$$

The resulting neutron energies in the laboratory system are tabulated below. G is the center-of-mass solid angle correction as given in Marion and Ginzburg.

$E_{\text{MeV}}^{\text{lab}}$	θ_n°	E_n^{MeV}	ϕ_n	G	E_n	ϕ_n	G	E_n	ϕ_n	G	E_n	ϕ_n	G
		Ground State			1.63 Mev level			4.25 Mev level			4.97 Mev level		
1.50	0°	11.99	0	.961	10.40	0	.952	7.84	0	.942	7.13	0	.940
	15°	11.97	15.4	.962	10.38	15.4	.953	7.82	15.4	.944	7.11	15.4	.942
	30°	11.91	30.7	.966	10.33	30.7	.958	7.76	30.9	.950	7.06	30.9	.948
	45°	11.83	46.0	.972	10.24	46.0	.966	7.70	46.2	.959	7.00	46.2	.957
	60°	11.70	61.2	.980	10.13	61.2	.976	7.60	61.5	.971	6.91	61.5	.969
	75°	11.57	76.4	.990	10.01	76.4	.987	7.49	76.7	.985			
2.00	0°	12.52	0	.947	10.93	0	.942	8.35	0	.933	7.64	0	.924
	15°	12.50	15.4	.949	10.91	15.4	.944	8.33	15.5	.936	7.62	15.6	.927
	30°	12.43	30.8	.954	10.82	30.9	.950	8.28	31.0	.942	7.57	31.1	.934
	45°	12.32	46.1	.963	10.74	46.2	.959	8.19	46.4	.952	7.48	46.6	.946
	60°	12.18	61.4	.972	10.60	61.5	.971	8.07	61.7	.966	7.38	62.0	.962
	75°	12.03	76.5	.986	10.46	76.7	.985	7.94	76.9	.983	7.25	77.2	.980

Neutron Energies for the Reaction $F^{19}(d,n)Ne^{20}$

E_d Mev	Θ_n^o lab	E_n Mev ϕ mp G			E_n Mev ϕ n G			E_n Mev ϕ n G			E_n Mev ϕ n G		
		<u>5.64 Mev level</u>			<u>6.17 Mev level</u>			<u>6.75 Mev level</u>			<u>9.34 Mev level</u>		
1.50	0	6.47	0	.935	5.95	0	.933	5.38	0	.931	2.81	0	.907
	15	6.46	15.5	.938	5.94	15.5	.936	5.36	15.5	.934	2.79	15.7	.910
	30	6.40	30.9	.944	5.89	31.0	.942	5.32	31.0	.940	2.77	31.5	.919
	45	6.35	46.3	.954	5.83	46.4	.952	5.26	46.5	.950	2.72	47.1	.933
	60	6.26	61.6	.968	5.74	61.7	.966	5.18	61.8	.965	2.66	62.5	.953
	75	6.16	76.8	.984									
2.00	0	6.99	0	.928	6.46	0	.924	5.88	0	.924	3.30	0	.898
	15	6.97	15.6	.931	6.44	15.6	.927	5.86	15.6	.927	3.29	15.8	.902
	30	6.92	31.1	.938	6.39	31.1	.934	5.82	31.1	.934	3.25	31.6	.911
	45	6.83	46.5	.949	6.31	46.6	.946	5.74	46.6	.946	3.20	47.2	.927
	60	6.73	61.8	.964	6.21	62.0	.962	5.65	62.0	.962	3.13	62.7	.948
	75	6.61	77.0	.981				5.54	77.2	.980			

Neutron Energies for the Reaction $F^{19}(d,n)Ne^{20}$ (continued)

E_d Mev	Θ_n° lab	E_n Mev	ϕ_n°	g	E_n	ϕ_n	g
		9.97	Mev	level	10.61	Mev	level
1.50	0	2.80	0	.890	2.17	0	.873
	15	2.79	15.7	.893	2.16	15.9	.877
	30	2.77	31.5	.904	2.14	31.7	.889
	45	2.72	47.1	.921	2.10	47.4	.909
	60	2.66	62.5	.944	2.05	63.0	.935
2.00	0	2.67	0	.888	2.02	0	.871
	15	2.66	15.9	.891	2.01	16.0	.876
	30	2.62	31.8	.902	1.97	32.0	.888
	45	2.57	47.5	.919	1.94	47.9	.908
	60	2.51	63.0	.942	1.88	63.5	.934
	75		78.4	.970	1.81	78.9	.966

Neutron Energies for the Reaction
F19(d,n)Ne20 (continued)

APPENDIX II

Angular Distribution Data for the Reaction $\text{Be}^9(\text{d},\text{n})\text{B}^{10}$

Angular distribution data in the laboratory system for neutrons leading to the 5.16 and 5.11 Mev levels of B^{10} are given in Tables II-1 and II-2 respectively. The three run numbers give the month, the day, and the sequential run numbers for that day, respectively. Because of the duration of the runs (approximately 1/2 hour each) and minor experimental difficulties, the distribution measurements were not made during a single day. Slight changes in dc levels or beam positions on the target on different days can cause serious changes in the yield and true-to-chance ratios. Because of this, it is difficult to estimate accurately the expected error in the data, especially for measurements of neutrons to the weakly populated 5.16 Mev level. Statistical error is usually less than the day-to-day reproducibility.

The data were normalized to a fixed counter distance, using only the inverse square law, and to a fixed integrated target current. The data were also corrected for changes in the relative efficiency of the neutron counter with neutron energy. This correction has been obtained by means of the $\text{T}(\text{p},\text{n})\text{He}^3$ reaction, which yields mono-energetic neutrons. Relative cross sections were obtained from Brolley and Fowler (Br 60). $\text{T}(\text{p},\text{n})\text{He}^3$ runs were made with the neutron counter at 10° to the incident proton beam, and with a neutron flight path of 1 meter. Proton bombarding energies of from 1.30 to

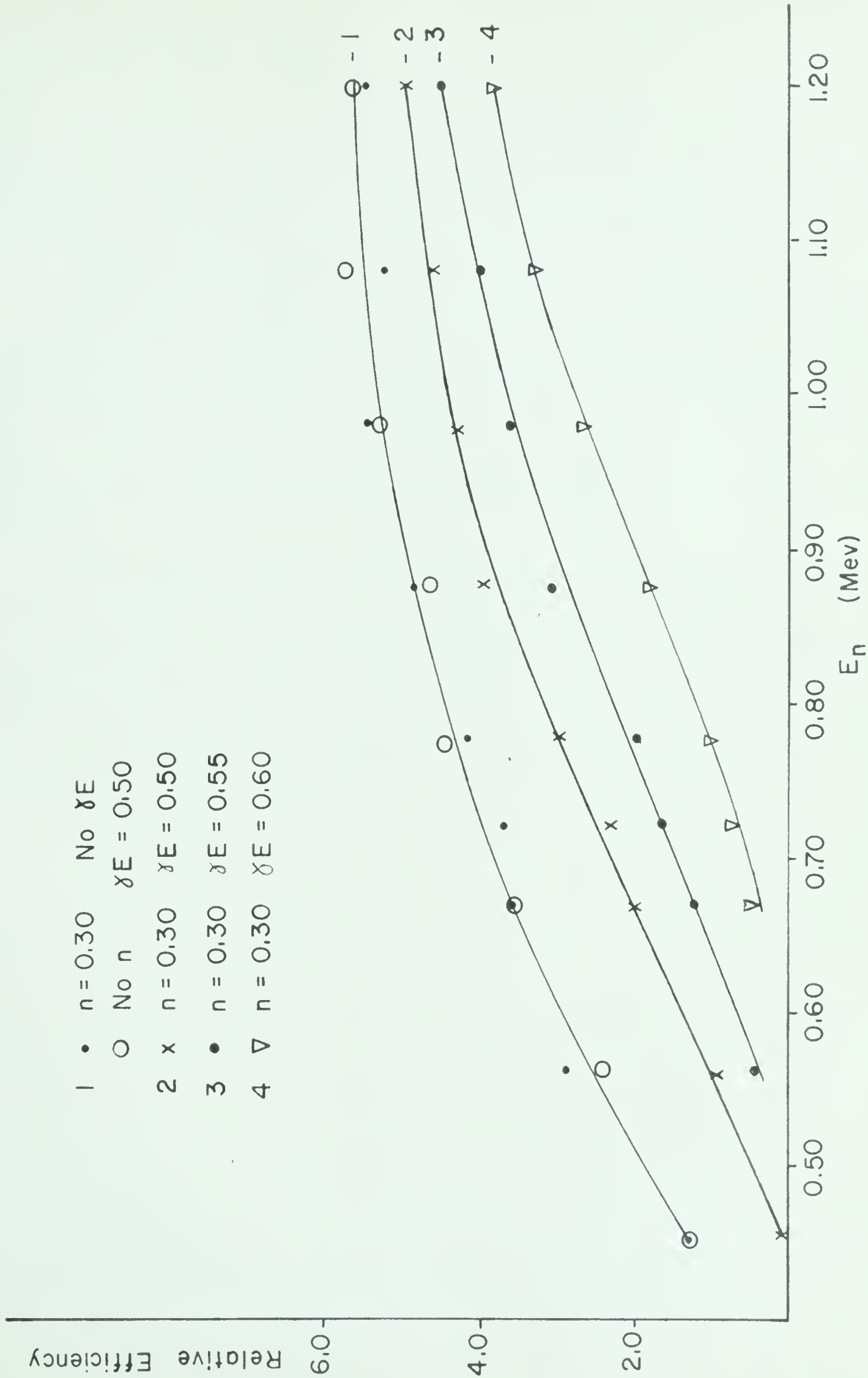


Figure 2-1 Relative efficiency of the neutron counter as a function of neutron energy.

2.00 Mev were used. Neutron energies were obtained from Marion and Allen (Ma 55). The resulting relative counter efficiency versus neutron energy curves are shown in Figure 2-1. At the bias settings used in the measurement of angular distributions of neutrons from the 5.16 and 5.11 Mev states (Neutron side channel = 0.30; gamma side channel = 0.60) the relative efficiency for neutrons to the 5.16 Mev level decreased by a factor of 2 between 0° and 60° .

Table II-3 shows angular distribution data for neutrons leading to the unresolved 5.16, 5.11 doublet, and to the 4.77 Mev level. The data have been normalized in the same way as the data in Tables II-1 and II-2. The energy of neutrons to the 5.11 Mev level has been used in reading efficiency corrections from Figure 2-1 for neutrons to the unresolved doublet.

The tables of Marion and Ginzburg (Ma 54) have been used for the transformation of the angular distribution data from the laboratory to the center of mass system. Calculated values of the variable x are .2137, .2058, and .1733 for neutrons to the 5.16, 5.11, and 4.77 Mev levels, respectively, at $E_d = 1.91$ Mev, and .1824 for neutrons to the 4.77 Mev level at $E_d = 1.50$ Mev.

Run No.	θ_n lab	μc	5.16 counts	S_n meters	$S_n = 5.6m$	40 μc	Average	Eff'y Correction	Norm Counts
3-21-3	0°	60	167±25	5.60	1.00	112	144	1.00	144±20
3-20-8		60	295±50	5.63	1.01	197			
3-20-9		60	184±25	5.63	1.01	124			
3-20-1	5°	20	167±15	5.24	0.876	117		1.00	149±20
3-20-11		40	146±20	5.70	1.03	150	149		
3-21-6		48.4	218±28	5.60	1.00	180			
3-20-4(b)	10°	80	298±30	5.24	0.876	130		1.02	160±20
3-20-7(b)		60	264±40	5.66	1.02	179	157		
3-21-2		40	163±25	5.62	1.0	163			
3-20-2	15°	40	171±25	5.24	0.876	151		1.03	161±25
3-20-12		60	310±50	5.62	1.0	206	156		
3-19-10		35	145±25	4.58	.669	111			
3-20-5	20°	40	100±25	5.24	0.876	140		1.06	150±20
3-21-7		50.7	236±30	5.42	0.937	142			
3-20-10		57.7	161±25	5.61	1.00	111			
3-21-1	25°	40	153±20	5.07	.821	126		1.12	152±20
3-20-13		33	121±20	5.62	1.0	146	136		
3-21-5		50	236±30	5.0	.796	150			
3-17-7	30°	40	143±20	4.1	.535	76	116	1.17	136
3-22-2		60	217±30	5.14	0.843	121			
3-20-6		60	146±20	5.24	.876	86	86	1.22	102±15
3-17-1	35°	40	146±20	4.1	.535	78	78	1.33	104±15
3-17-2		40	62±20	4.1	.535	33	33	1.43	47±20
3-17-3		40	118±20	4.1	.535	63	63	1.59	100±15
3-23-3	60°	49.1	169±40	3.0	.289	39	39	2.0	78±15

TABLE II-1. Be⁹(d,n)B¹⁰. Angular distribution data in the laboratory system for neutrons to the 5.16 Mev level. $E_d = 1.91$ Mev.

Run No.	On^0 lab	μc	5.11 counts	Sn meters	Sn=5.0 meters	Eff. 40mc	Norm. counts
3-21-3	0	60	2753	5.60	3441	2305	
3-17-5		20	2277	4.1	1528	3056	
3-20-8		60	3212	5.63	4079	2733	2821
3-20-9		60	3328	5.63	4099	2733	
3-24-14		40	2549	5.24	2804	2804	
3-19-11	5	20	1410	4.58	1184	2368	
3-19-12		40	2377	5.24	2615	2615	
3-20-1		20	1113	5.24	1224	2448	2613
3-20-11		40	2029	5.70	2638	2638	
3-21-6		48.4	2876	5.60	3624	2995	
3-17-6	10	40	3606	4.1	2416	2416	
3-20-4(b)		80	4022	5.24	4424	2212	
3-20-7(b)		60	2842	5.66	3638	2437	2309
3-21-2		40	1378	5.62	1764	1764	
3-19-10	15	35	1775	4.58	1491	1700	
3-20-2		40	1583	5.24	1741	1741	1811
3-20-12		60	2379	5.62	2974	1992	
3-17-4	20	40	2560	4.1	1715	1715	
3-20-5		40	1350	5.24	1485	1485	
3-20-10		57.7	1768	5.61	2210	1534	1634
3-21-7		50.7	1920	5.42	2246	1765	
3-22-1		40	1427	5.42	1670	1670	
3-20-13	25	33	637	5.62	796	963	
3-21-1		40	790	5.07	814	814	890
3-17-7	30	40	1225	4.1	821	821	
3-21-5		50	1037	5.0	1037	829	
3-22-2		60	1045	5.14	1097	735	752
4-3-4		50	778	5.0	778	622	
3-20-6	35	60	583	5.24	641	430	450
3-17-1	40	40	540	4.1	362	362	406
3-17-2	45	40	397	4.1	266	266	318
3-17-3	50	40	203	4.1	136	136	173
3-23-3	60	49.1	483	3.0	174	142	227

TABLE II-2 Be⁹(d,n)B¹⁰. Angular distribution data in the laboratory system for neutrons to the 5.11 Mev level. $E_d = 1.91$ Mev.

θ_n° lab	Doublet Counts/ 2μ	Corrected Counts	4.77 Counts/ 2μ	Corrected Counts
-10	6654	5880	498	308
-5	7286	6193	536	328
0	7478	6543	576	358
0	7712	6640	520	320
5	7446	6329	476	295
10	6490	5740	534	331
15	5684	5060	612	380
20	4270	3928	534	338
30	2274	2274	646	413
40	1302	1433	760	500
45	912	1086	770	508
60	491	786	679	495
60	837	837	963	582
75	612	857	917	544
90	355	710	767	564
90	718	893	852	530
105	351	655	759	508
120	106	594	539	420
135	64	240	473	402

TABLE II-3 $\text{Be}^9(d,n)\text{B}^{10}$. Angular distribution data for neutrons leading to the 5.11, 5.16 doublet and to the 4.77 Mev level. $E_d = 1.91$ Mev.

The following table gives coincidence time-of-flight data obtained during the partial width measurement of the 5.16 Mev level of B^{10} . Spectra for neutrons leading to the 5.16 Mev state in B^{10} and to the 6.40 Mev state in C^{11} were recorded using a 1 meter flight path and a deuteron energy of 1.91 Mev. For comparison with the pulsed beam measurements, the data have been normalized to 5.1 meters using the inverse square law, and divided by the absolute gamma-ray efficiency.

Run No.	Bias Energy	Neutron Group	Counts/ 50 μ c	Gamma-ray Efficiency	"Normalized" Counts
4-3-5	.28 Mev	6.48	925	15.3×10^{-3}	2370+100
4-3-6	.28 Mev	5.16	121	35.1×10^{-3}	135+ 20
4-5-1	.58 Mev	6.48	802	14.3×10^{-3}	2160+100
4-5-2	.58 Mev	5.16	93	18.2×10^{-3}	193+ 30
4-5-5	0.82 Mev	6.48	862	13.5×10^{-3}	2440+100
4-5-6	0.82	5.16	77	14.3×10^{-3}	208+ 30
4-5-4	1.42	6.48	719	11.4×10^{-3}	2420+100
4-5-3	1.42	5.16	32	8.98×10^{-3}	140+ 20
4-5-10	2.62	6.48	543	8.16×10^{-3}	2540+100
4-5-11	2.62	5.16	10	2.39×10^{-3}	150+ 20

APPENDIX III

Gamma-ray Efficiencies for the NE 102 Phosphor

The gamma-ray detection efficiency of the NE 102 phosphor used in the neutron time-of-flight spectrometer was measured by comparing its counting rate with the counting rate from a NaI crystal. The NE 102 counter was mounted close to the target chamber in the same position as when used in neutron time-of-flight work. A collimated 4 inch by 4 inch NaI crystal was mounted on the other side of the target holder as shown in Figure 3-1. Since the gamma-ray detection efficiency of the NaI crystal was reasonably well-known (Mi 61), the absolute efficiency of the NE 102 phosphor was determined from a direct comparison of the counting rates of the two detectors. No attempt was made to evaluate the solid-angle of the NE 102 phosphor.

The pulse-height distribution spectrum from the NaI crystal was displayed directly on the 256 channel pulse-height analyzer. NE 102 counting rates were measured above given discriminator settings of the gamma side-channel. Since the discriminator settings were calibrated in terms of gamma-ray energy, the efficiency of the counter as a function of bias energy could be determined. The discriminator setting versus gamma-ray energy scale was defined by means of 0.51, 0.662, 1.28, 2.62, and 6.14 Mev gamma-rays. For high energy gamma-rays, the energy scale was non-linear, making it difficult to obtain an accurate energy scale above 2.62 Mev. This non-linearity was caused largely by saturation in the photomultiplier (see Figure 3-2), which was normally operated at high dynode potential differences for best time resolution.

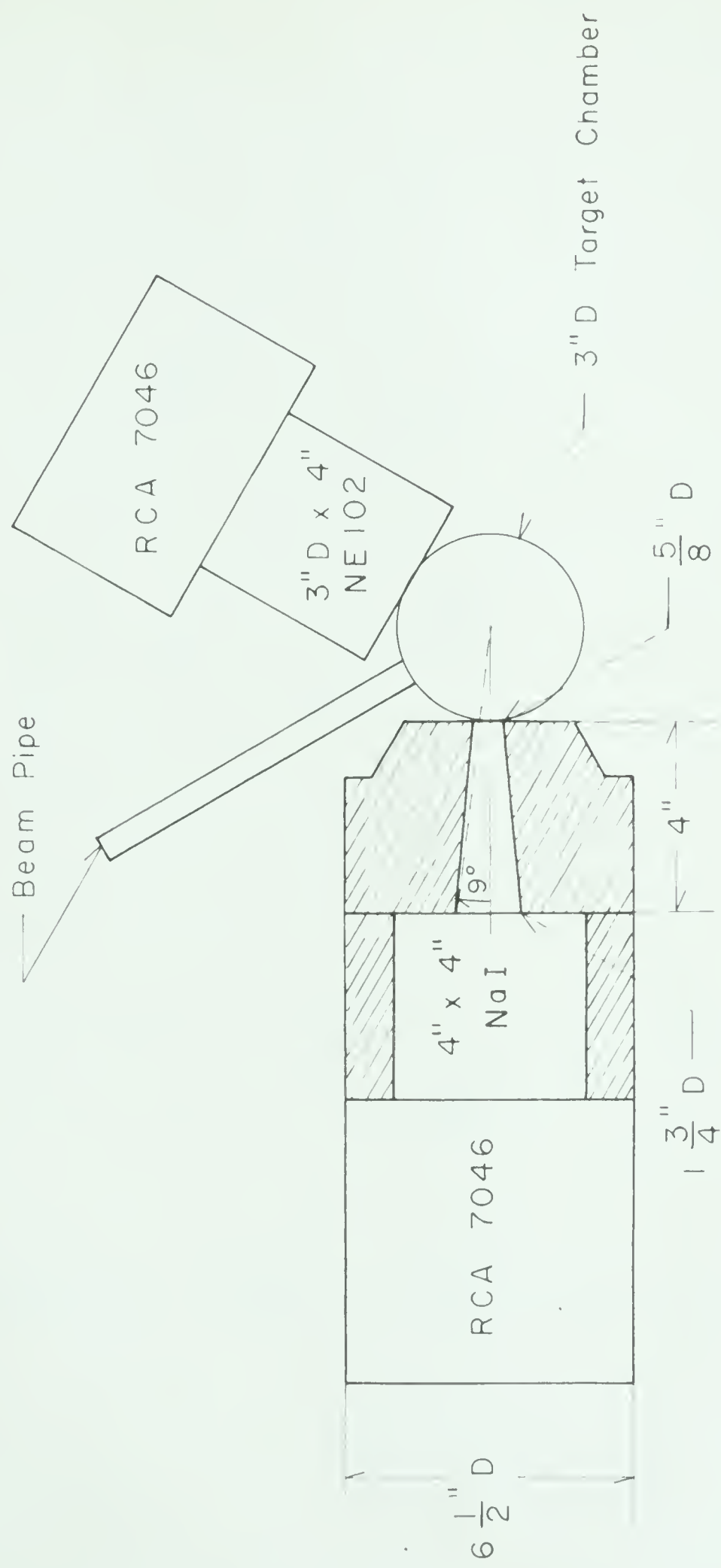


Figure 3-1 Geometry for the measurement of the gamma-ray efficiency of the NE 102 counter.

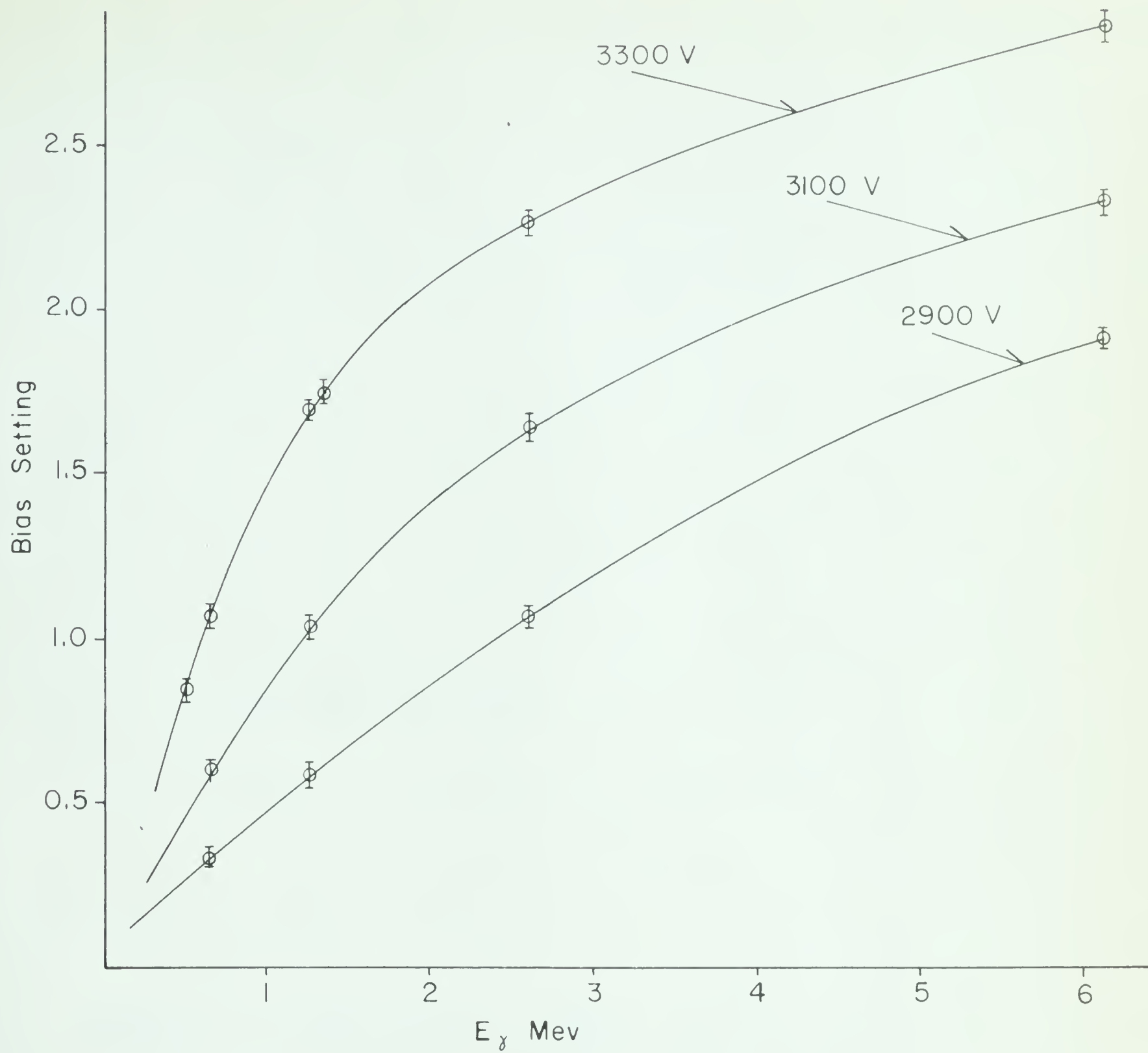


Figure 3-2 Gamma-ray bias curves for the NE 102 counter.

The efficiency measurements were carried out using gamma-ray energies of 6.14, 2.62, and 1.28 Mev. First, the 6.14 Mev gamma-rays were obtained by means of the 340 kev resonance in the $F^{19}(p,\gamma)O^{16}$ reaction. The target was then removed from its holder and replaced in a succession by RdTh and Na^{22} sources. In all cases background counting rates were subtracted from the observed counting rates to obtain the true counting rates.

The half-angle θ of the NaI collimator was 9° . Therefore, the solid angle seen by this crystal, given by $\omega = A/R^2 = 2\pi(1 - \cos \theta)$ is 0.077 steradians. Total NaI detection efficiencies, ϵ , were taken from curve 1(a), page 32, of Miller's thesis (Mi 61). The gamma-ray spectra used are shown in Figure 3-3. Contributions to the spectra from contaminant gamma-rays, such as the 0.51 Mev line in the RdTh spectrum, were subtracted. That is, for each gamma-ray, the ratio $S = \frac{\text{true spectrum counts}}{\text{total spectrum counts}}$ was determined. The total source strength for each gamma-ray was then defined by

$$C = (4\pi/\epsilon\omega) \times S \times (\text{observed counting rate})$$

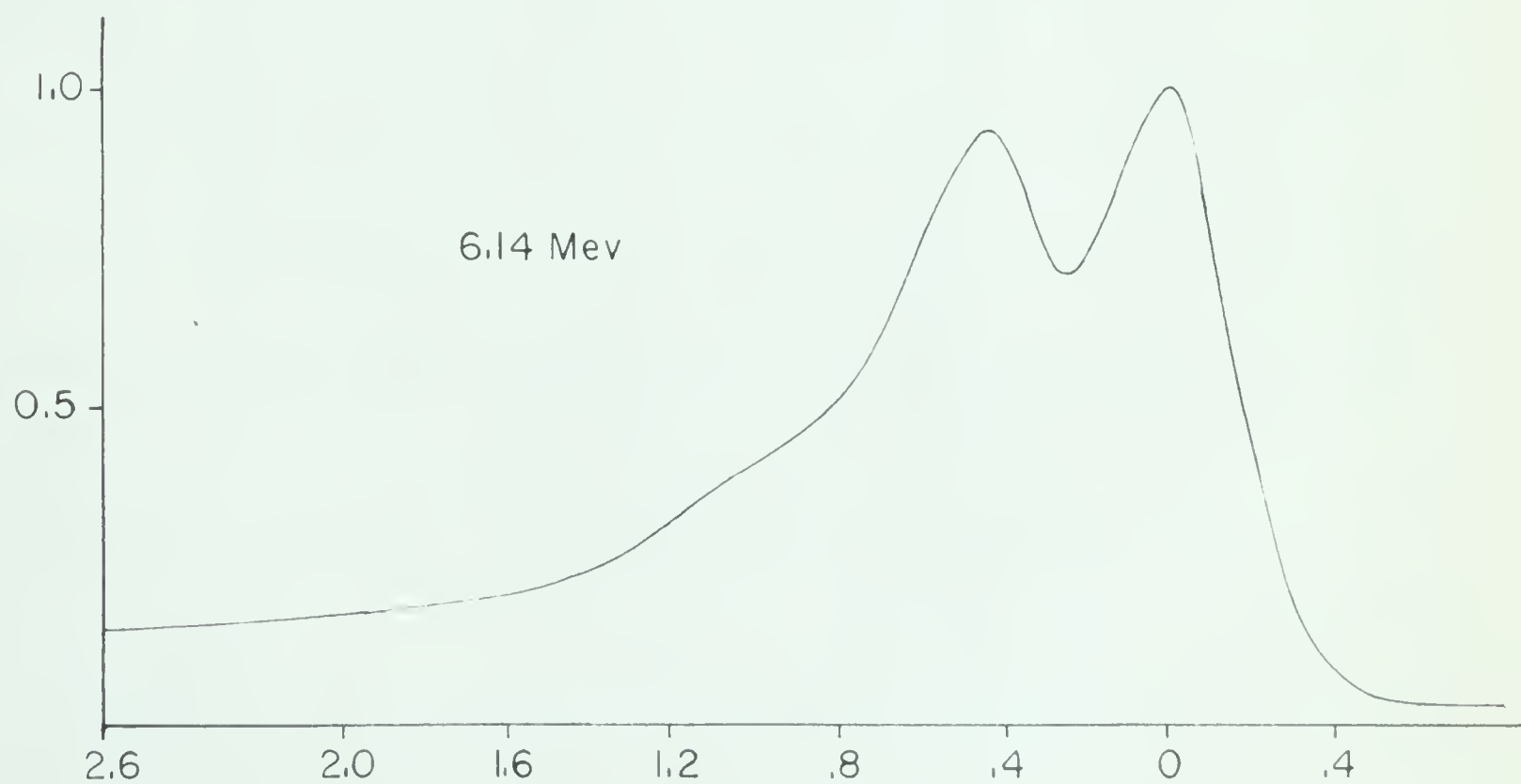
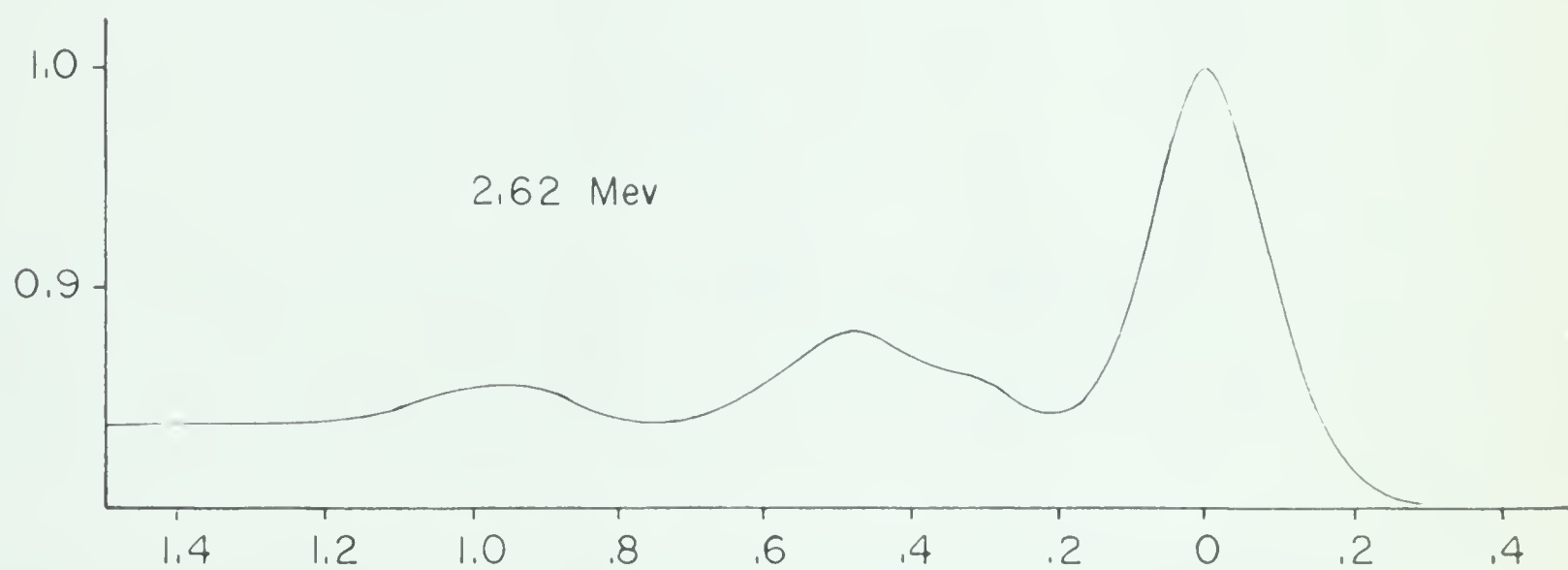
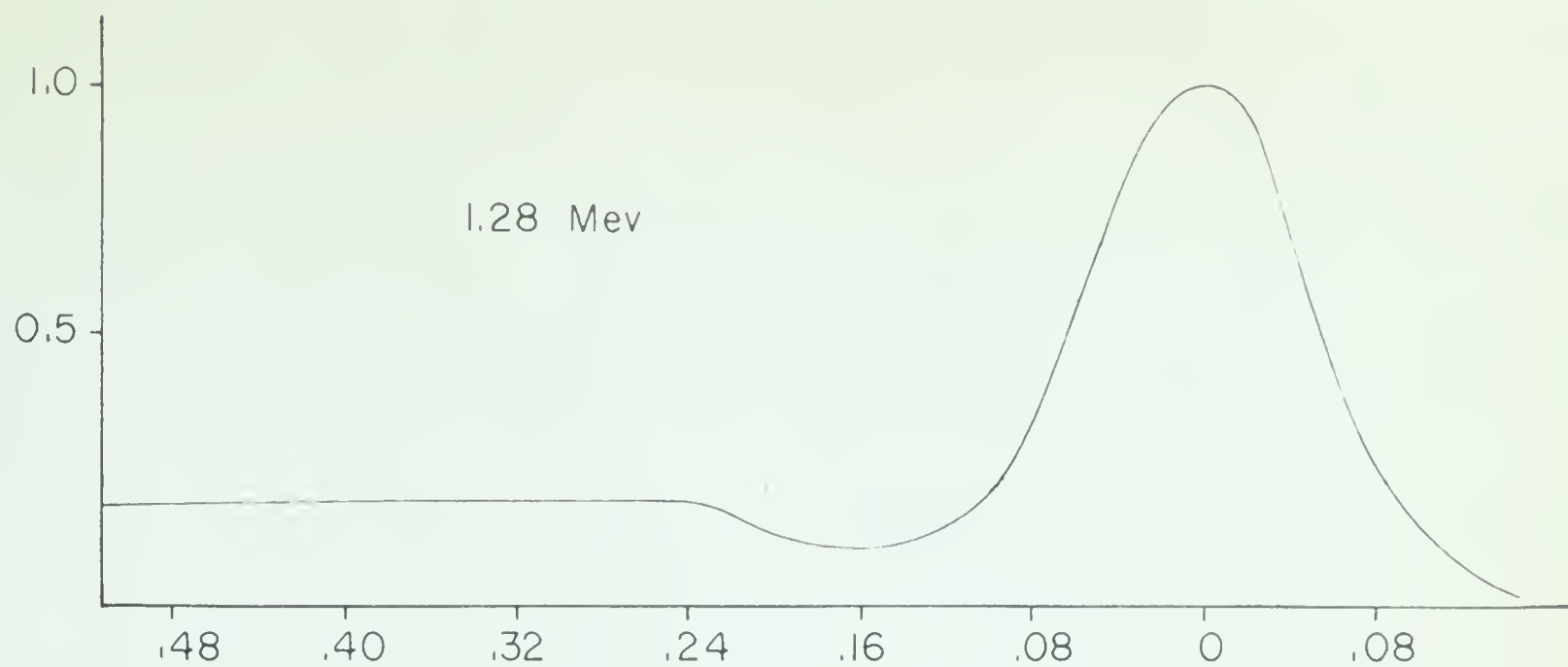
$$= K \times (\text{observed counting rate}).$$

The following results were obtained:

Gamma-ray Energy	Detection Efficiency	$\epsilon\omega/4\pi$	S	K
1.28	89.1%	.00546	.484	88.6
2.62	77.6%	.00476	.507	106.5
6.14	73.3%	.00449	.914	203.6

The absolute efficiency of the NE 102 counter, defined above a given bias energy, was calculated from the ratio

$$\frac{\text{NE 102 counting rate}}{\text{NaI counting rate} \times K}$$



Mev from Full-Energy Peak

Figure 3-3 Gamma-ray spectra for the collimated 4 inch by 4 inch NaI crystal.

The resulting absolute efficiencies for the NE 102 counter are shown in Figure 3-4. The efficiency curves are nearly linearly decreasing functions of gamma-ray bias energy, as is expected since the gamma-ray absorption occurs mainly through Compton scattering.

The measured efficiencies were checked by a crude theoretical calculation. The total absorption of gamma-rays in passing through 4 inches of NE 102 was first evaluated. The composition of NE 102, as quoted by Nuclear Enterprises Ltd., is

H	0.054	$\times 10^{24}$	atoms/cm ³
C	0.048	$\times 10^{24}$	atoms/cm ³
N	1.8	$\times 10^{18}$	atoms/cm ³
O	1.8	$\times 10^{18}$	atoms/cm ³

Absorption due to nitrogen and oxygen was neglected due to their low content. Absorption coefficients for hydrogen and carbon were taken from Davisson and Evans (Da 52). The calculations are summarized below:

E (Mev)	a cm ² /atom	a_{μ} cm ² /atom	(N x a_{μ}) cm ⁻¹	μ cm ⁻¹	E
1.36	H .181 $\times 10^{-24}$	.181 $\times 10^{-24}$	.0098		
	C 1.083 $\times 10^{-24}$	1.084 $\times 10^{-24}$	.0520	.0618	46.6%
2.63	H .125 $\times 10^{-24}$	.125 $\times 10^{-24}$	.0068		
	C .747 $\times 10^{-24}$	.761 $\times 10^{-24}$	.0365	.0432	35.5%
6.13	H .072 $\times 10^{-24}$	.0735 $\times 10^{-24}$	.0040		
	C .433 $\times 10^{-24}$	.482 $\times 10^{-24}$	.0231	.0270	24 %

$\mu = a_{\sigma} + a_{\kappa} + a_{\tau}$, where a_{σ} is the Compton scattering cross section due to Compton, photo-electric, and pair-production processes. N is the number of atoms per cm².

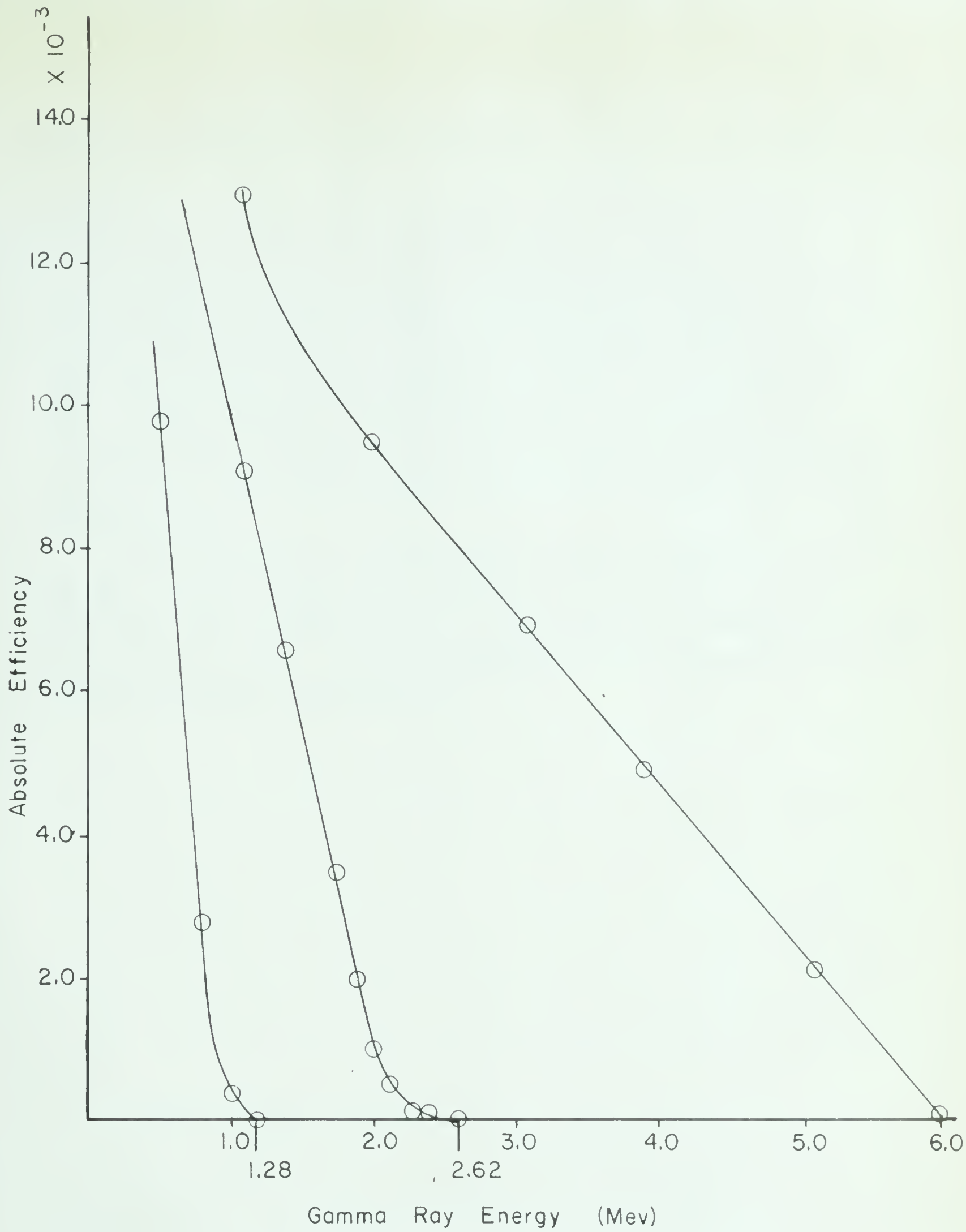


Figure 3-4 Absolute gamma-ray efficiencies for the NE 102 crystal.

Then $E = \text{absorption in the phosphor} = \frac{I_0 - I}{I_0} = 1 - e^{-\mu x}$

where $x = 10.16$ cm. For all cases $\sigma \approx a\mu$, so that the only significant absorption process is Compton scattering.

To calculate the absolute efficiency, it was necessary also to know the solid angle of the crystal. The solid angle was estimated from the cross-sectional area of the phosphor taken at a point mid-way along its axis. This assumption gave a solid angle of 0.855 steradians. The detection probabilities, $(0.855/4\pi \times E)$ for the gamma-ray energies of 1.36, 2.63, and 6.13 Mev were then .0316, .0241, and .0163 respectively.

Extrapolation of the measured energy versus efficiency curves to zero energy gave absolute efficiencies of .024, .019, and .015 respectively for the gamma-ray energies of 1.28, 2.62, and 6.14 Mev, in fair agreement with the results of the crude theoretical calculation.

APPENDIX IV

Data Obtained During the Measurement of the Decay of the 6.48 Mev State in C^{11}

I. Gamma-ray Spectrum Shapes

For the analysis of the coincidence spectra recorded in Chapter IV, it was necessary to determine the response of the NaI crystal for a number of pure gamma-rays. The gamma-ray energies used were 4.33 Mev, obtained from the $N^{15}(p,\alpha\gamma)O^{16}$ reaction at $E_p = 895$ kev, 6.14 Mev, obtained from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction at $E_p = 610$ kev, and 7.886 Mev, obtained from the $Si^{30}(p,\gamma)P^{31}$ reaction at $E_p = 620$ kev. The observed spectrum shapes are shown in Figure 4-1. The relative spectrum height is shown plotted versus the number of Mev from the full energy peak. Spectra for 4.65, 6.5, 7.0, and 8.9 Mev gamma-rays were predicted by interpolation by D. W. Braben of this laboratory; the derived spectra are shown in Figure 4-2. From the spectrum shapes, the relative efficiency for any part of the gamma-ray spectrum can be determined. For the present work it has been assumed that the detection efficiency of the crystal for gamma-rays is constant in the energy region 4 to 9 Mev; curve 1(a), page 32 of Miller's thesis (Mi 61) shows that this assumption is well justified.

II. Experimental Results

The experimental results are summarized below. Row 8 is proportional to the observed total to random counting ratio, since coincidence counts in the 7.4 to 10 Mev region are random in origin. Between runs I and II, the total

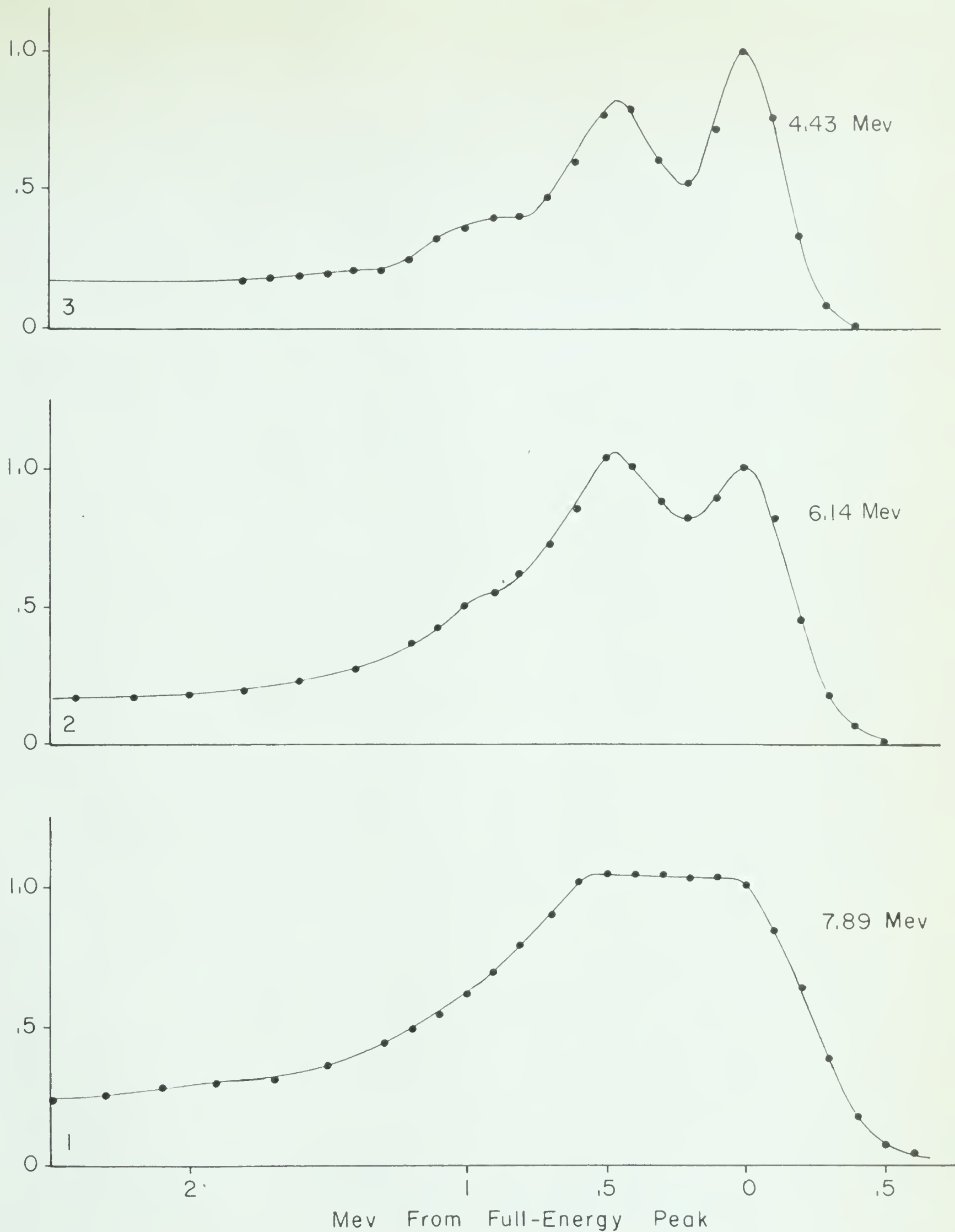


Figure 4-1 Gamma-ray spectra for the 4 inch by 4 inch NaI crystal.

1. $\text{Si}^{30}(\text{p}, \gamma)\text{P}^{31}$, $E_p = 677 \text{ kev}$, $E = 7.89 \text{ Mev}$
2. $\text{F}^{19}(\text{p}, \alpha \gamma)\text{O}^{16}$, $E_p = 610 \text{ kev}$, $E = 6.14 \text{ Mev}$
3. $\text{N}^{15}(\text{p}, \alpha \gamma)\text{C}^{12}$, $E_p = 895 \text{ kev}$, $E = 4.43 \text{ Mev}$

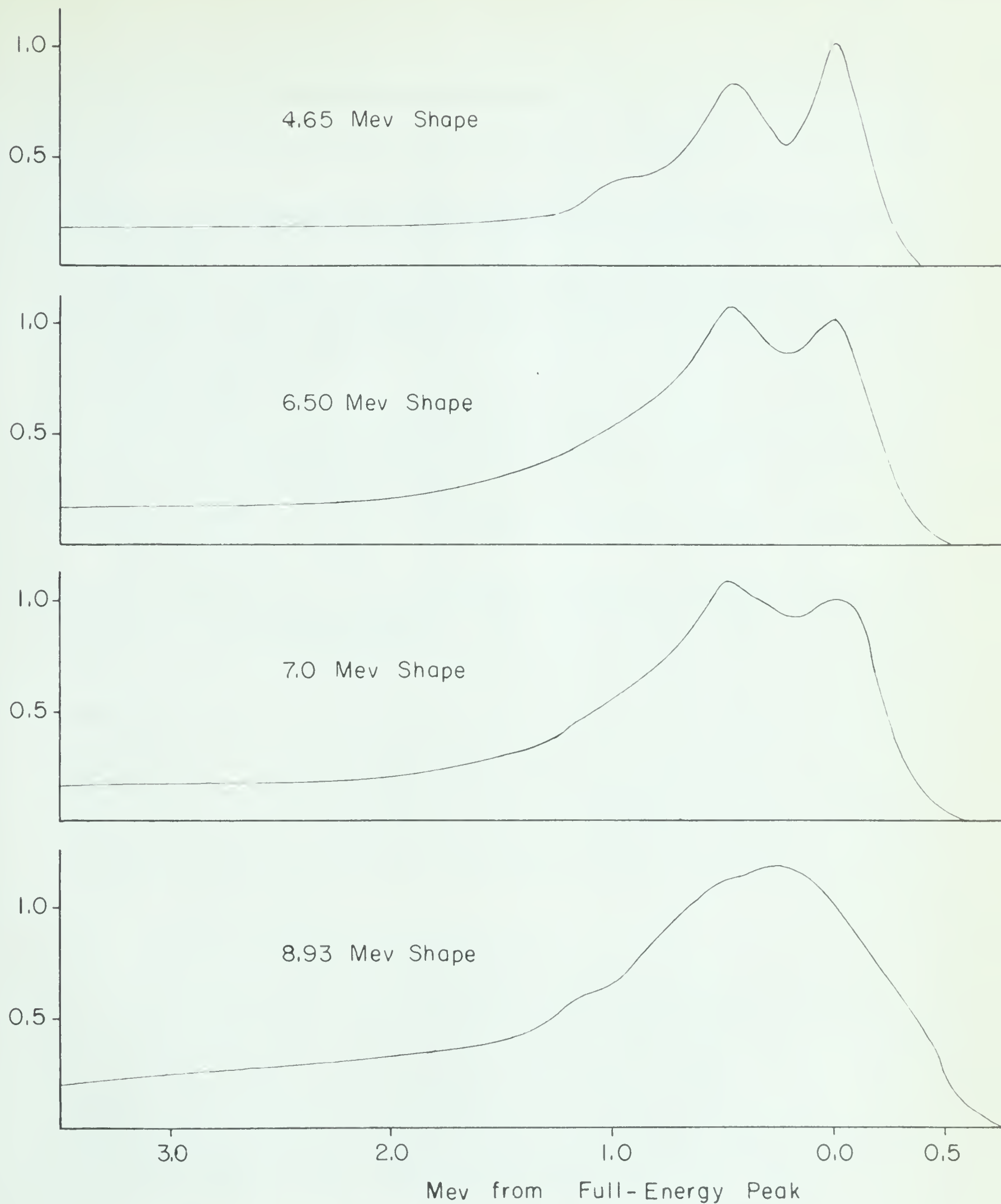


Figure 4-2 Derived gamma-ray spectra for the 4 inch by 4 inch NaI crystal.

Row No.		Run No.			
		I	II	III	IV
1	θ_n lab	30°	30°	0°	-30°
2	Neutron flight path	50 cm.	50 cm.	40 cm.	40 cm.
3	Time of run, minutes	60	149	321	133
4	Total gamma-ray counting rate 1-10 Mev	5000/sec.	2500	2000	2000
5	Neutron counting rate to the 6.48 Mev state	140/sec.	60/sec.	50/sec.	80/sec.
6	Coincidence counts 3-10 Mev	7752	4997	6016	4655
7	Coincidence counts 7.4-10 Mev	369 ± 20	64 ± 8	113 ± 10	80 ± 9
8	Ratio $\frac{3-10 \text{ Mev counts}}{7.4-10 \text{ Mev counts}}$	21	87	53	58

counting rate from the target was reduced by a factor of 2; as expected the coincidence counting rate was reduced by a factor of 4. However, the random counting rate was reduced by a factor of 16. Possibly severe low-energy "pile-ups" due to neutron-iodine reactions were occurring in the NaI crystal during run I.

III. Branching Ratio Calculations

Branching ratio calculations for the decay of the 6.48 Mev level have been carried out using three different criteria, X, Y, and Z, for the estimation of random counts. For X the random counting rate is assumed to be zero. For Y the expected random pulse-height distribution spectrum is assumed to be the same as the ungated NaI spectrum. For Z the

estimation of the random counts is based on the ungated spectrum shape after subtraction of contributions from 6.48 Mev gamma-rays. For criteria Y and Z the number of coincidence counts in the energy interval from 7.4 to 10 Mev has been used as the basis for normalization since counts in this interval are random counts. The subtraction of 6.48 Mev contributions from the ungated spectrum for criterion Z has been carried out as indicated by Figure 4-3. The resulting spectrum, together with the coincidence gamma spectrum recorded during run II, is shown in Figure 4-4.

The spectrum shape data used for the calculations are given below. The energy scale has been divided into 3 intervals, (A) extending from 3 to 4.85 Mev, (B) from 4.85 to 7.4 Mev, and (C) from 7.4 to 10 Mev.

	A 3 - 4.85 Mev	B 4.85 - 7.4 Mev
Ungated NaI spectrum	Ratio $\frac{A}{C} = 2.86$	Ratio $\frac{B}{C} = 2.19$
Ungated, with 6.5 Mev subtracted	Ratio $\frac{A}{C} = 2.69$	Ratio $\frac{B}{C} = 1.48$
"Pure" 6.5 Mev line	Ratio $\frac{A}{\text{Total}} = 0.163$	Ratio $\frac{B}{\text{Total}} = 0.60$
"Pure" 4.3 Mev line	Ratio $\frac{A}{\text{Total}} = .622$	-----

The branching ratio calculations are indicated by Table IV-1. There is no significant difference between the branching ratios calculated using criterion Y and those calculated using criterion Z.

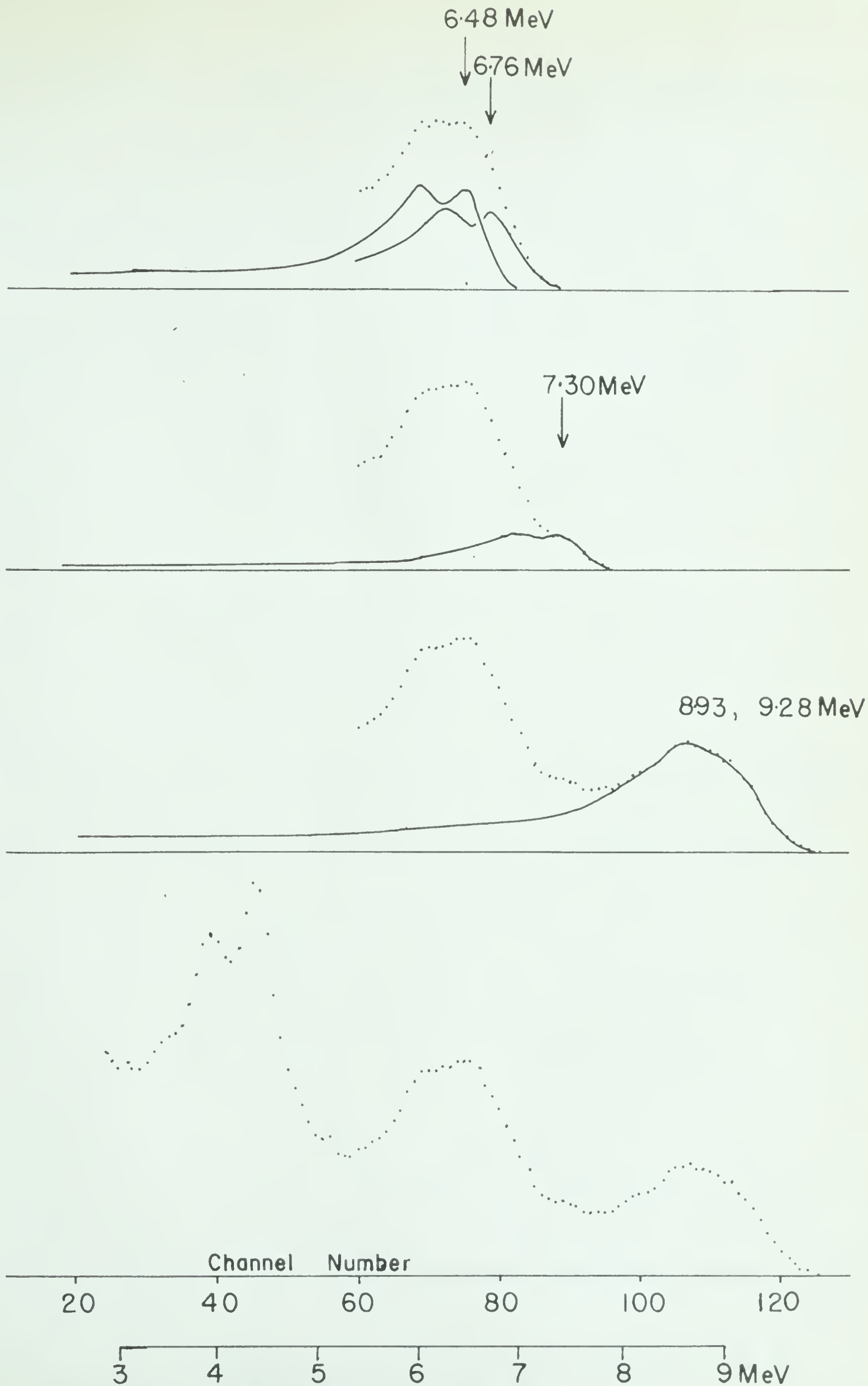
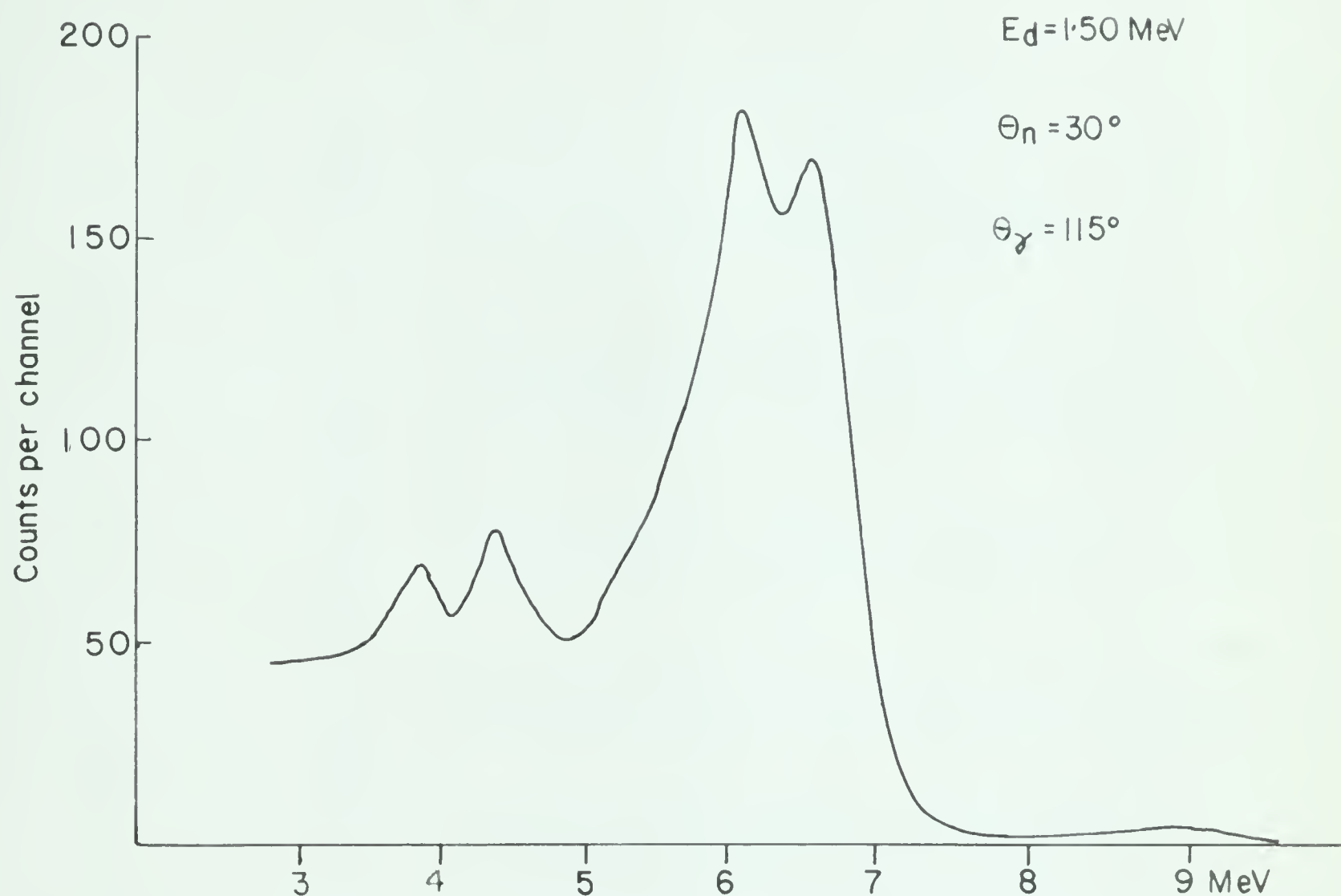
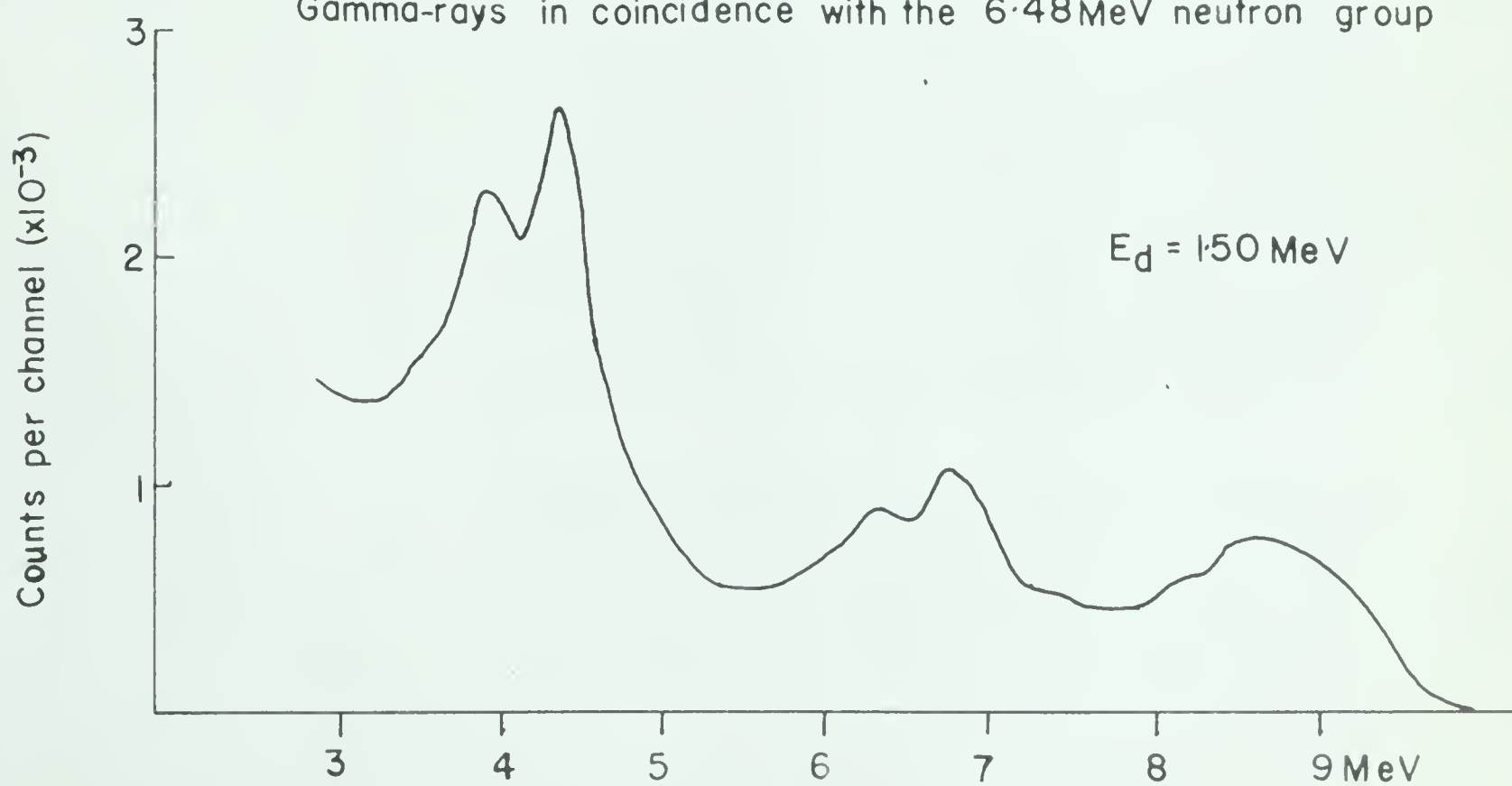


Figure 4-3 The subtraction of 6.5 MeV gamma-rays from the ($B^{10} + d$) ungated gamma-ray spectrum.

Figure 4-4 Gamma-rays from the deuteron bombardment of B^{10} with the 6.48 Mev line subtracted.



Gamma-rays in coincidence with the 6.48 MeV neutron group



Gamma-rays from the deuteron bombardment of B^{10}

(6.48 MeV line subtracted)

Random "Criterion"	Run No.	Randoms in A	Genuine in A	Randoms in B	Genuine in B	6.48 Total	6.48 in A	4.26 in A	4.26 Total	Ratio $\frac{6.48}{4.26}$
	I	0	2660	0	4723	7872	1280	1380	2219	3.6
	II	0	1470	0	3263	5438	886	584	939	5.8
X	III	0	2172	0	3731	6218	1013	1159	1863	3.3
	IV	0	1385	0	3190	5317	867	518	833	6.4
	I	1055 +50	1605 +100	808 +50	3915 +120	6538 +150	1065 +30	540 +130	869 +180	7.5 +1.5
	II	183 +20	1287 +70	140 +15	3123 +70	5215 +100	850 +20	437 +90	703 +120	7.4 +1.5
Y	III	323 +30	1849 +80	247 +20	3484 +70	5818 +100	948 +20	901 +100	1450 +150	4.0 +0.5
	IV	229 +20	1156 +70	175 +20	3015 +70	5035 +100	821 +20	335 +90	539 +130	9.3 +2.0
	I	171 +20	1300 +70	95	3170 +50	5280 +80	862 +40	438 +60	702 +100	7.5 +1.1
	II	990 +60	1670 +100	547 +40	4176 +70	6960 +130	1136 +60	533 +100	857 +160	8.1 +1.5
Z	III	304 +30	1868 +80	167 +20	3564 +70	5940 +100	968 +40	900 +120	1447 +150	4.1 +0.8
	IV	215 +30	1170 +70	118 +20	3072 +55	5120 +100	835 +40	335 +70	538 +110	9.5 +2.0

TABLE IV-1. Calculation of Branching Ratios for the Decay of the 6.48 Mev State of C^{11} .

APPENDIX V

A Search for the 6.345 Mev Level of C^{11}

The level in C^{11} at 6.345 Mev was not observed until recently, although a mirror nucleus comparison of B^{11} and C^{11} had indicated for some time that a level was missing in C^{11} at about 6.5 Mev excitation. This level was found at 6.345 Mev by Hinds and Middleton (Hi 61), through magnetic spectrometer analysis of deuterons produced in the $B^{10}(He^3,d)C^{11}$ reaction at 9.84 Mev bombarding energy. The intensity of the 6.345 Mev state, up to angles of 80° in the center of mass system, was always less than 5% of the intensity due to the 6.48 Mev level. The 6.34 Mev state has also been observed by James et al (Ja 61b) in a study of the reaction $B^{10}(d,n)C^{11}$ using neutron time-of-flight techniques. The deuteron energy was 1.2 Mev, and the flight path was 3.5 meters. The observed intensity of the 6.34 Mev state, at center of mass angles of 25° and 80° , was about 10% of the intensity of the 6.48 Mev level. Neilson et al, in this laboratory, have tentatively observed the 6.34 Mev level using time-of-flight techniques. The intensity of neutrons to this state has been found to be less than 5% of the intensity to the 6.48 Mev level (Ne 61).

A brief search was made for the 6.34 Mev level in C^{11} by looking for a neutron group adjacent to the 6.48 Mev line produced in the $B^{10}(d,n)C^{11}$ reaction. The pulsed deuteron energy was 1.9 Mev, and the flight path was 4.4 meters. Spectra recorded at laboratory angles of 30° , 45° , 60° and 75° are shown in Figures 5-1 and 5-2. The low intensity neutron group

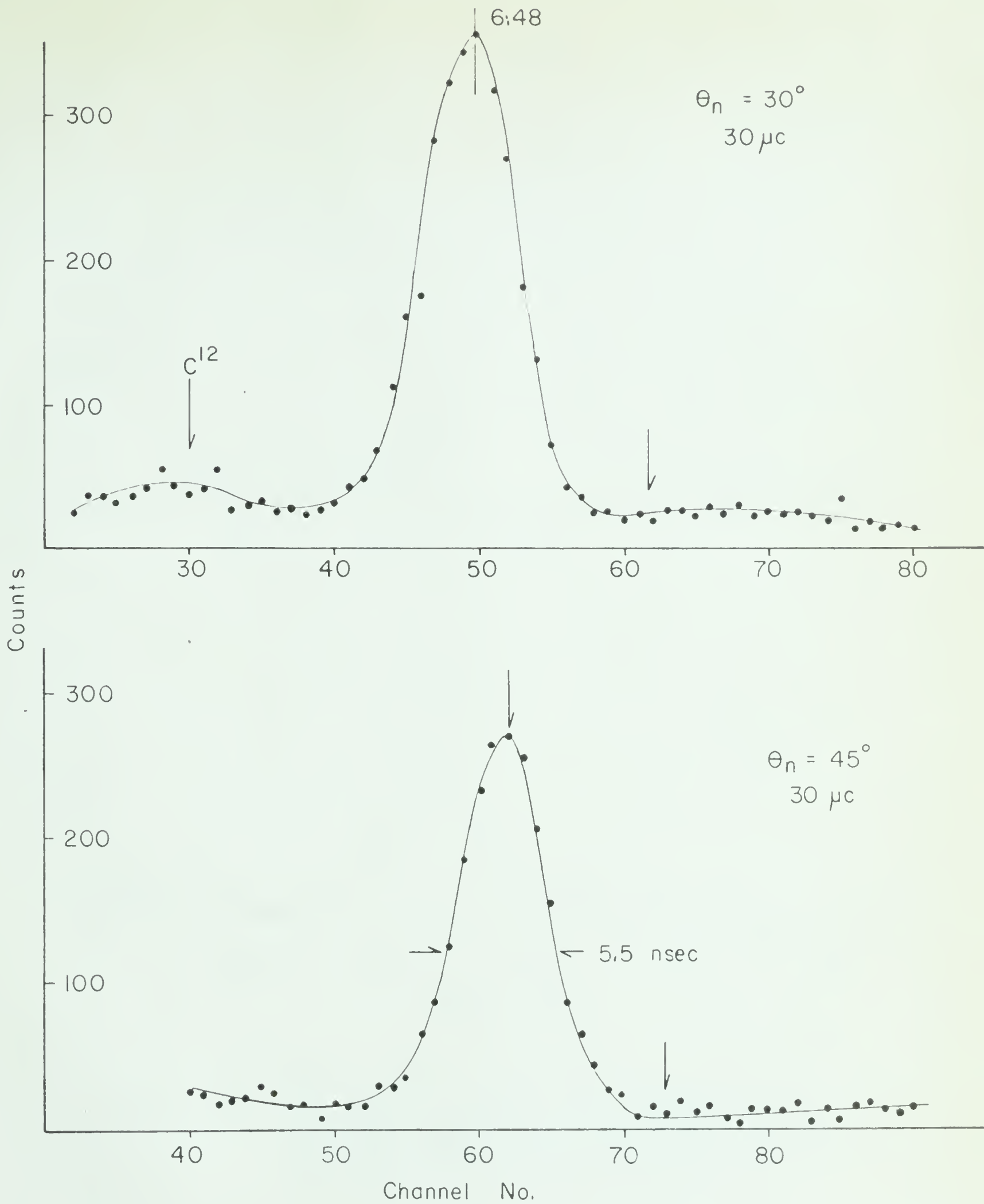


Figure 5-1 $B^{10}(d,n)C^{11}$. Neutrons leading to the 6.48 Mev state in C^{11} . $E_d = 1.9$ Mev, $S_n = 4.4$ meters.

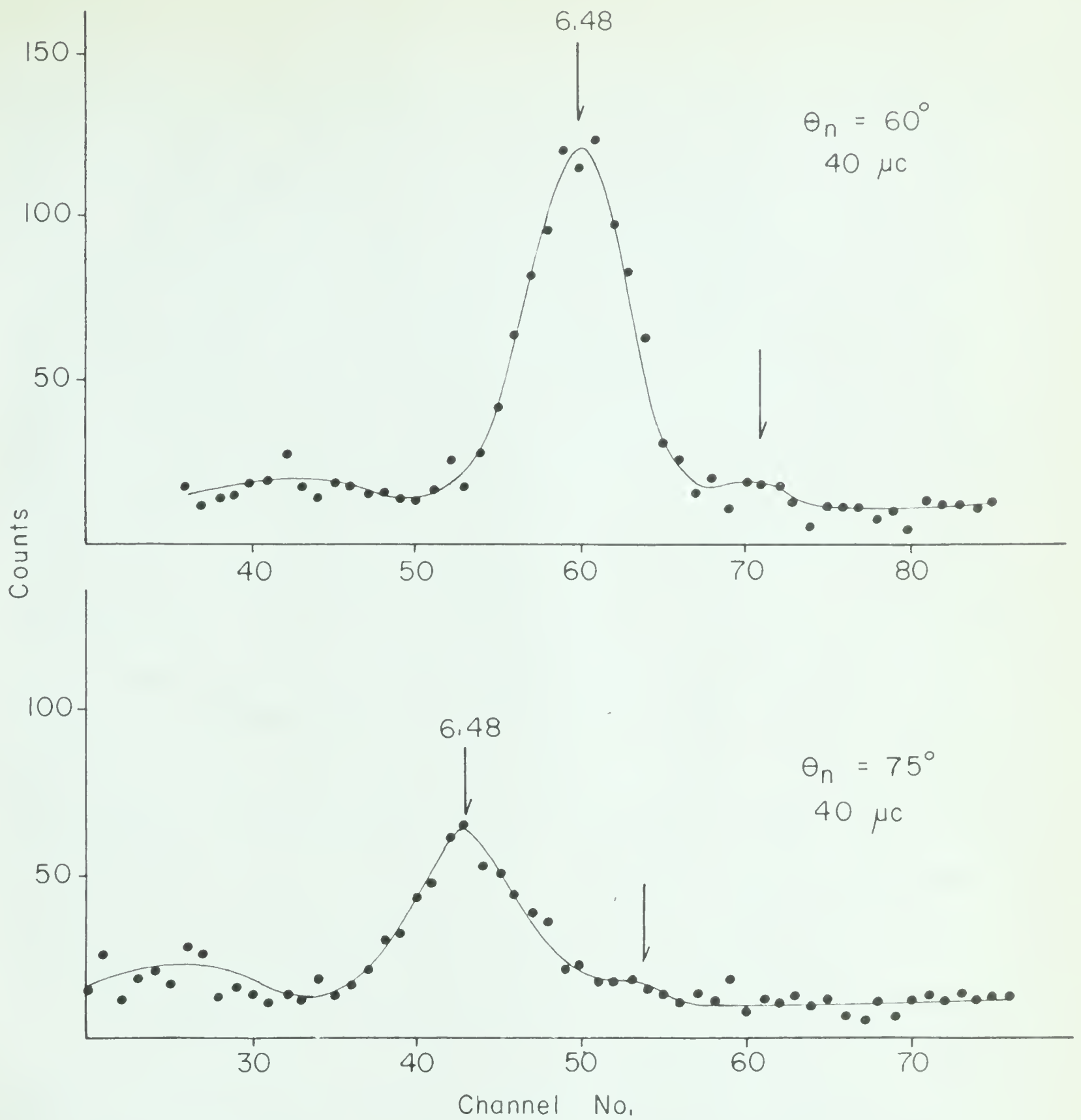


Figure 5-2 $B^{10}(d,n)C^{11}$. Neutrons leading to the 6.48 Mev state of C^{11} . The unmarked arrows indicate the expected location for neutrons leading to the 6.345 Mev state of C^{11} .

to the left of the 6.48 line is probably caused by carbon in the B^{10} target. The arrows in Figures 5-1 and 5-2 indicate the expected location of the 6.34 line relative to the 6.48 line. The time scale is 0.85 nsecs per channel. There is no indication of 6.34 Mev state in C^{11} in the 30° and 45° spectra, but there is evidence for this state in the 60° and 75° spectra. An intensity of neutrons to the 6.34 Mev state of 10% of the intensity of neutrons to the 6.48 Mev state should have been easily observable in the 30° and 45° spectra; the 6.34 Mev level would not have been seen if this ratio were less than 5%. At 30° and 45° in the laboratory system the yield of neutrons to the 6.48 Mev level is nearly a maximum, but decreases by more than a factor of 2 between 45° and 60° . Since Hinds and Middleton observed little change in the yield to the 6.34 Mev state between 0° and 80° , the failure to observe the 6.34 Mev level at 30° and 45° in the present work is not completely unreasonable. In the 60° and 75° spectra the intensity of neutrons tentatively identified as leading to the 6.34 Mev state is between 5 and 10% of the intensity to the 6.48 Mev state. However, further measurements using different counter angles and flight paths are necessary for positive identification of this state.

The experimental time resolution for neutrons leading to the 6.48 Mev state in C^{11} in the above spectra was 5.5 nsecs. A time resolution of 3 nsecs should have been obtained. The B^{10} target thickness was 80 ugm/cm^2 , which is expected to correspond to an energy loss of some 30 kev for 1.9 Mev deuterons. The contribution of target thickness to the time resolution, given by $\frac{\Delta E}{E} = \frac{2\Delta t}{t}$ should have been only 2 nsecs for the 4.4 meter flight path.

A rough check was made on the target thickness by recording gamma coincidence spectrum of neutrons to the 6.48 Mev state at

flight paths of 1 meter, 2 meters, and 3 meters. The deuteron energy was 1.91 Mev, and the counter angle was 30° . The spectra had respective time resolutions of 3.8, 4.2, and 4.6 nsecs, indicating that at large flight paths the neutron energy spread caused by the target thickness did contribute significantly to the time resolution. The target thickness was assumed not to contribute significantly to the time resolution at 1 meter; that is, the resolution due to other causes was taken to be 3.8 nsecs. Then if the contributions to the time resolution due to the target thickness at 2 meters and 3 meters are Δt_2 and Δt_3 , then

$$\Delta t_2 = \sqrt{4.2^2 - 3.8^2} = 1.8$$

$$\Delta t_3 = \sqrt{4.6^2 - 3.8^2} = 2.6$$

using $\frac{\Delta t}{t} = 1/2 \frac{\Delta E}{E}$, with $E = 1.78$ Mev, for which

$$t = 54.2 \text{ nsecs per meter,}$$

$$\Delta E = 59 \text{ kev from } \Delta t_2$$

$$\text{and } \Delta E = 57 \text{ kev from } \Delta t_3.$$

The determination of target thickness is very crude, but it does indicate that the target is considerably thicker than 30 kev. If the target thickness actually is 60 kev, the expected contribution to the time resolution is 4 nsec, which could explain the poor time resolution.

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